Learning from master's muscles: EMG-based bio-feedback tool for augmenting manual fabrication and crafting

by

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Submitted to the Department of Architecture
in partial fulfillment of the requirements for the degree of
Master of Science in Architecture Studies
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2014

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Abstract

Learning a novel skill is a time consuming process and can be frustrating at times. It may require hours of supervised training before a minimum level of proficiency can even be attained. For example in ceramics, centering the clay on the pottery wheel is a challenging task, which must be mastered before one can even begin to create an object.

The objective of this thesis is to design and implement a wearable device that aids novices during the skill acquisition process of any such procedural motor task. The goal of the wearable device is to significantly reduce the amount of time needed to familiarize oneself with a new technique and medium, and to quickly attain a basic level of proficiency. This is achieved by providing students continuous visual feedback, which compares their on-going movements to that of a master craftsman performing the identical task recorded beforehand. Illuminated LEDs placed on the student's forearm relate movement kinematics, an accelerometer, magnetometer, gyroscope and muscle activity, all of which are recorded using electromyography (EMG) electrodes in real-time. The device thereby augments the sensory feedback available to the student during skill acquisition and enables them to correct their movements to match those of the master craftsman as an immediate reaction.

In pilot studies, the device was evaluated within the context of pottery wheel-throwing; specifically, forearm kinematics and muscle activation during the centering of the clay were investigated. Movement feedback and data are discussed in relation to the current theories on sensorimotor control and learning. The initial results were evaluated with respect to the amount of time taken to become comfortable with the skill at hand.

While there are a number of possible applications of the device, two main areas are discussed: 1) The device has the potential to become a disruptive technology, fundamentally changing traditional methods of learning and teaching arts and crafts, both in the studio/classroom environment and for autodidacts at home; 2) The device may have significant clinical impact in the field of neurorehabilitation and motor (re)education after a stroke or traumatic brain injury. Finally, an archive of expert performances for any given motor skill may be generated using the wearable device; an archive anyone could consult when learning a new skill whether it be out of curiosity or out of necessity.

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Acknowledgments

There are so many people who helped me and impacted me profoundly throughout the process leading up to this thesis. Now is my chance to thank them. First of all, I would like to express my gratitude to the members of my thesis committee for all their help and support throughout this period. Many thanks to my thesis advisors Takehiko Nagakura and Federico Casalegno for helping me to develop and deliver my ideas. I really appreciate their patience and support while working on delivering my thesis. I am also grateful to my thesis reader, Olliver Kannape for his feedback and comments. Cagri Zaman, for being one sharp guy one can always rely on for a healthy dose of critical and genuine desire to help and for teaching me a ton during the past two years; Will Langford for always being able to help me when I had no clue how to move forward; Carlos Gonzalez for his genuine desire to help, and for his camaraderie;members of the Biomechatronics Group, for being so kind and willing to help and answer all my question; the MIT SAA for allowing to conduct experiments in their space as well as providing a place where I could go and clear my mind; everyone that happily volunteered to help me run experiments; my family for their long-distance, rock-solid, unwavering support - I have been constantly thinking about them all; and finally, my beautiful girlfriend Caitlin, for being the most wonderful partner I could ever have, this thesis couldn't have been possible with out her.

-This thesis is dedicated to my family.

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Chapter 1

Introduction

If one is to explore the way in which long-term memory is developed through repetition, then one must first understand what is happening in the muscles and cognition. In this paper, the process in which we learn a motor skill is questioned, and whether or not it can be changed in a more efficient manner: can we augment the learning process by introducing a biofeedback loop into the knowledge acquisition processes of a motor skill? By augmenting the human sensory experience, is more "noise"[1]introduced into the process of learning or does it enhance the learning process? The method in which skills are learned has already begun to shift to a more tangible form of media with the popular video game 'Guitar Hero'. As opposed to the classical classroom setting where one learns through audio/visual stimulation only, 'Guitar Hero' allows the user to learn the skill of playing a guitar through the haptic senses. Coordination and rhythm is learned rapidly in an environment which more closely resembles the practice of the task at hand.

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[1] Noise: random or unpredictable fluctuations and disturbance of neural, neuromuscular or environmental origin.[36]

1.1 Motivation for generating a feedback loop

The idea of a wearable feedback loop is motivated by the increasing standardization of digital fabrication[2]. The use of technology in the world of architecture has been generally reduced to the use of 3D printers and Computer Numerical Control (CNC) milling devices. The majority of projects or models produced by such advanced machines have become monotonous and with a clear aesthetic as how it was made; the creators have lost the sense of craft and the idea of individuality and uniqueness.

Virtual environments are no longer something we project into the future; they are now part of the everyday lives of todays students, makers and designers. As a generation, we have been trained to work within this environment out of convenience; virtual environments provide immediate feedback and reaction while providing access to vast resources and an extreme level of precision. The ability to easily change things without the risk of wasting materials, funds, or time further reinforces the desire to work strictly within the virtual realm. When actions are executed in the physical world, visual instructions are the only form of information used in order to compare the action to the final result; when creating artifacts by hand, there is nothing to tell the user how efficiently to execute the task. It takes many years of experience to learn the movements necessary to create muscle memory. In the book Outliers, author Malcolm Gladwell says that it takes roughly ten thousand hours of practice to achieve mastery in a field. 10,000 hours of appropriately guided practice has been determined to be the magic number of greatness, regardless of a persons natural aptitude. Gladwell also states that the majority of those who drop the field of study do so in the first 2,000 hours of practice due to the steel nature of the learning curve at the start of the knowledge acquisition process. By introducing a technological advancement into this process, the shape of the learning curve could be altered in

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[2] Digital modeling and fabrication is a process that joins design with the Construction / Production through the use of 3D modeling software and additive and subtractive manufacturing processes. These tools allow designers to produce digital materiality, which is something greater than an image on screen, and actually tests the accuracy of the software and computer lines.

such a way that the new skill becomes more intuitive to the user as opposed to a challenge that needs to be conquered.

Figure 1-1 shows a direct comparison of the master craftsman and the novice performing the same task; creating a cylinder on the pottery wheel. It is clear that the master craftsman on the left has achieved a high comfort level with the medium, as seen by the tall, rigid walls of the cylinder. The student on the right has created an uneven and incomplete cylinder showing their lack of familiarity with the material and technique.

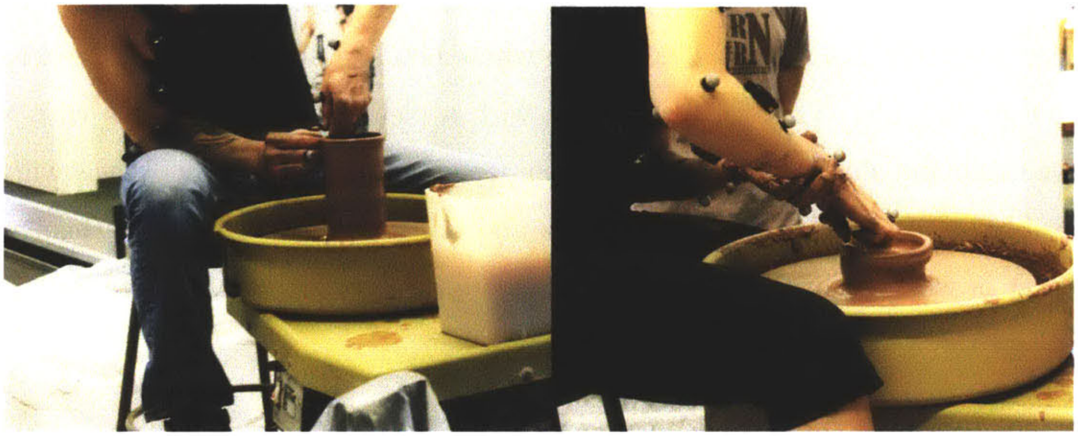

Figure 1-1: Object comparison between expert on the left and novice on the right

The knowledge of a craft used to be developed by the master craftsman, then passed down through generations by personal interaction with apprentices and students. This enviroment fosters care and consideration of the techniques needed for the craft at hand, and ultimately a deep love of the craft is developed through the personal relationship the student develops with both the master craftsman and the tools of the craft[25]. This form of learning is being rapidly replaced by the school of thought that digital fabrication is faster, easier, and cheaper than building something from scratch, by hand; that machines and technology are here to help students optimize their time and efficiency.

This way of thinking teaches students that machinery can and should be used to create something from start to finish, as opposed to using modern technology as a tool to help develop the project. Digital fabrication can in fact be faster and cheaper than building a project by hand, but it will most likely create something that is repetitive and not very unique. Technology can be used to augment the learning process to generate a new form of creation that pulls from both the experience of a master craftsman and the efficiency of technology: digital making.

I believe that we are on the face of the earth to improve our way of life and to preserve what our ancestors have developed and shared with us. We live in a time of constant change with a focus on innovating. In the not so far future, we will be able to have a better understanding of our own self and we will be able to interact with computers in a more seamless fashion where bits and atoms will be intertwined in our everyday life. This will provide us with a plethora of possibilities with the way we make and shape our world. The components mentioned in this thesis will be not visible to the eye, but the information and the way we interact with them will be. That is why I believe that we owe it to ourselves to start to explore and give technology the importance that it deserves now.

1.2 Purpose of this study

This study is looking to inform the learning process at some of the earliest stages of learning hand-made crafts, and in this case, ceramics. The intention is to develop a new feedback process by introducing awareness of bio-signals to the individual performing the task. Specifically, surface electromyography and motion tracking will be used as an input for data collection and visual feedback. This feedback will be presented to the user in a simple and clear manner, allowing them to better understand how well they are performing the task at hand without the need of an outside critic, instructor, or peripheral device.

When we use peripherals in the virtual environment, i.e. a mouse or remote, there is a certain level of disengagement that distances the user from the task at hand. What if you could use your body to monitor your movement and the degree of muscular stress or efficiency? This could potentially bring the level of precision that is so highly valued in the virtual realm into the physical and allow the users to create a more intimate bond with their work through the use of their own bodies as opposed to a peripheral device.

By implementing the wearable device developed through this thesis in an everyday environment, EMG[3] recordings could be downloaded through the internet, thus eliminating the need for an instructor. The recordings could be uploaded directly to the wearable device of the user looking to acquire the skill, allowing the user to directly compare his or her movements to those of the master craftsman whose data was recorded as the control set.

With the advanced computational power of algorithms, muscle activity can be tracked in order to recreate motor skills using robotics and prostheses, as well as augmented reality in the virtual environment. Various forms of interaction allow the user to select their preferred method of learning in order to meet their goal. This could be out of necessity due to an injury or simply a new skill that the user would like to acquire. By using an EMG, one would be able to monitor the electronic signals that the body naturally produces in order to create reinforced feedback loops for advanced learning or interaction.

The use of reinforced feedback loops mirror the sensory motor control of the master, in which the user can alter their technique in order to more efficiently execute the task[36]. The goal of this system is to drastically shorten the length of time it takes for the user to familiarize themselves with the technique, material and craft while using their own body as a learning tool.

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[3] Electromyography is a technique for evaluating and recording the electrical activity produced by skeletal muscles.

1.3 Why craft?

According to Grey and Burnett in their paper Making Sense, craft is described as a dynamic process of learning through material and sensory experience leading to a broader understanding[24],[31]. In craft and design, visual and material artifacts and tools have a central role in mediating the thinking and making processes[9][18]. Craft can also be seen as a form of embodied knowing that involves materials, tools and social communication. Making is an embodied way of thinking that works as an anchor for linking the mind and body, with emphasis on understanding the relationship of the body to the process of making and thinking, i.e., how artisans relate their bodies, tools, materials and space in their work setting. This thesis by no means proposes that feedback will teach people how to be creative or replicate an experience or aesthetic; it acknowledges the value of working with your hands and encourages thinking through making. What it proposes is to reduce the time that it takes to become familiar with a new medium. It encourages creativity while it takes away some of the handicaps that might be present at the early stages of working with a medium.

1.4 Research method in brief

The basis of this thesis was founded in the desire to link the courses I have taken through my education at MIT. Through these courses, I have gained extensive knowledge of physics, coding, and hardware development. The education in these topics provided by MIT encouraged further research into hardware components and how they can be better utilized in every day life. Integrating technology into daily tasks became the primary topic of research and it is at this point that I learned of the capabilities of the EMG.

This research will employ different tools in order to collect the most accurate and relevant data when working on a hand-made craft to allow the user to record and evaluate their technique to further the craft.

The sequence in which I developed my interest in the topic of biofeedback loops and augmenting the learning process is as follows:

1. I first began researching neurophysiological signals produced by the body. Through this research, I learned of the study of electromyography and furthered my knowledge of collecting data from the body.

2. The data that the body produces is highly redundant, so the next step was to develop an algorithm that allows me to collect the data so that I may organize and evaluate at a later date.

3. Processing the data coming from the EMG sensor required a great deal of time and effort due to the vast amount of data produced. It quickly became apparent that the Arduino that was previously processing the data was far too slow and too small. For this reason, I upgraded the component to a Teensy 3.1 32 bit ARM processor, which far exceeded the capabilities of the Arduino. Where the Arduino had only 32 kilobytes of storage, the Teensy has 256 kilobytes available for data storage. This allowed the device to read and record data at a much faster rate, thus allowing the analysis to be performed at a much faster rate.

4. It became clear to me that a wearable device would be the vehicle in which I would be able to collect the most accurate form of data from the human body. I began prototyping a device that would fit close to the body, with areas of concentration to better monitor specific muscle movements. To allow the EMG circuit to have the possibility to be used in an every day manner, a series of experimental materials were generated using 3D modeling software and a MakerBot Replicator 2 3D printer. Both rigid and flexible materials were created using this technique. The flexible material had the capability to be formed into an armband containing the LED visual display. Store-bought conductive fabric was sewn into a compression sleeve in order to create electrodes over the forearm muscles. The goal of this sleeve was to be able to monitor the signals being sent through the muscles using the EMG without having to apply adhesive electrodes before every experiment. The fabric compression sleeve allowed

the user to easily slide on the electrodes at the start of the experiment and off at the conclusion.

5. The flexible fabric, EMG device and Teensy microprocessor joined to create a visual display to allow the user to properly evaluate their technique while performing a motor skill, and adjust accordingly to better execute the task. On the wrist along with 3 strips of LEDs that illuminate to show the user their progression in learning the task at hand, there is a 9DOF (Accelerometer, Magnetometer and Gyroscope-all of them 3 axis) and a 6DOF sensor positioned on the armband near the biceps muscle. These two motion sensors are used to generate direction and orientation of the arm. A program written in Arduino language is then loaded to the Teensy microprocessor where the signal processing and all the computation occurs. A mini SD card is used to store and to read data from the sensors while the system runs in real time. This allows the system to compare the user's data to that of a master craftsman, therefore allowing the user to correct themselves during the learning process.

6. To have a control set of data to test the newly collected data against, I brought into the project a master craftsman in the area of ceramics and learned how ceramic artists perform certain tasks. I then measured his muscular movement when performing the tasks and recorded his bio-signals using an electromyograph.

7. In order to compare the data collected from the master craftsman to the data I intended to collect from test subjects, I generated a program that analyzes the data collected, compares it to that of the previously recorded master craftsman. It then creates a visualization for the user to see and understand, thus creating the feedback loop.

8. I then gathered a group of participants whom I could test the program through the wearable device. Each participant worked with clay for a limited time while wearing the device, thus allowing me to collect a range of data while the

participants performed the same task.

9. A conclusion can be made through the analysis of data collection to determine whether the wearable device has a significant impact on the speed in which the user can familiarize theselves with the technique and craft at hand. The evaluation of the device is qualitative in that it can only be evaluated through the user and their experience while performing the desired task. Each experiment provided the subject with a clear task at hand to be completed using the assistance of the EMG device. The length of time each participant took to complete the task was recorded with each iteration. Multiple iterations were completed with slight changes to the parameters of the code in order to better accommodate the learning curve of each participant. By lowering the tolerance of the parameters, the participant found it easier to meet the goal of the task at hand, be it completing the motions in a shorter time frame or matching the position of the previous recording while performing the task.

1.5 Previous studies using Bio-signals

There is a trend in current computerized architectural design practice that encourages the embodiment of computing, meaning the body is the medium in which data is collected. As we move forward with disruptive technology (modern-day smart phones and other devices that quickly age and become obsolete after only a few years), having a body centralized system that can produce accurate and constant signals could allow for an extremely stable datum where we could learn more about the body without changing it[30]. By ridding the educational environment from complex instructions and concentrating on optimizing those that are frequently used, substantial increases in performance can become a reality.

During the 1960's, Paul Bach-y-Rita was one of the first to experiment with the signals produced by the human body[1]. He experimented with sensory substitution that illustrated the brain's plasticity by enhancing certain areas when one or several modalities were injured. He created a device in which a camera records what is seen through glasses, and then transforms the image into electric impulses. The image is then 'flashed' onto the body via a tactile display. The subject's tactile sensitivity and tactile skills grow through training of the tactile sense due to the inability to utilize the visual modality, thus proving the brain's ability to overcome what could be interpreted as a disability. It has been proven that the body can adapt through the use of it's own signals; it is my goal to decrease the length of time it takes to do so.

A modern example of using bio-signals for educational use is the R-Cloud developed by the Department of Electrical and Electronic Systems at the Saitama University in Japan. The project consists of a chair with an exoskeletal arm that provides aided movement to patients undergoing rehabilitation. Pneumatic muscles provide assisted movement to an injured appendage and a display in front of the patient allows the user to visualize which muscle is used during their therapy. The patient is then able to focus their energy on the rehabilitation of a very specific area of the body.

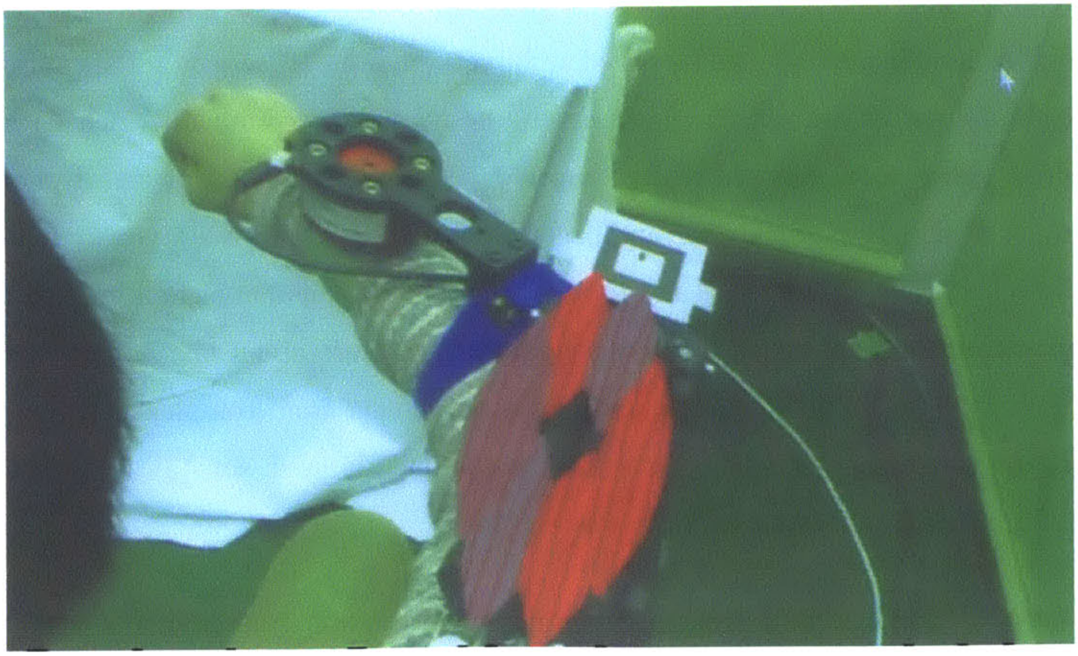

Figure 1-2: Augmented reality showing active muscle during rehabilitation.

Chapter 2

Background

2.1 Section Overview

The background of this thesis is divided into two major sections. The first section describes the physiology of the human arm, outlines bio-signal processes, and introduces key terms and assumptions central to the thesis. The second section provides a historical review of experiments on humans learning new skills, specifically working on a pottery wheel.

2.2 Muscle Memory

Muscle memory is a term commonly used in everyday discourse for the sort of embodied implicit memory that unconsciously helps us to perform various motor tasks we have somehow learned through habituation, either through explicit, intentional training or simply as the result of informal, unintentional, or even unconscious learning from repeated prior experience.[32]

It is a known fact that it takes time and effort to learn motor skills, whether they are everyday tasks such as walking which is learned at a very young age, or more complicated tasks such as playing a musical instrument. The practice of somaesthetics emphasizes the idea that cultivating bodily practices heightens our sensations and perceptions of the world around us; they also encourage us to be more in control and more caring of the self[28]. The idea that one's own body can teach itself how to better control itself is central to my thesis. Where somaesthetics discusses the use of actions like Tai Chi or Yoga to help center the mind and the body, I feel the same sense of self-informing can occur through the introduction of a technological device.

2.3 Anatomy of the Human Forearm

In the forearm there are two bones: the radius and the ulna. The radius and the ulna are connected with the wrist from the side of thumb and small finger respectively. The ulna is longer and has a stronger connection with the brachial region than the radius, however the radius creates a stronger contribution to the movements associated with the wrist joint.

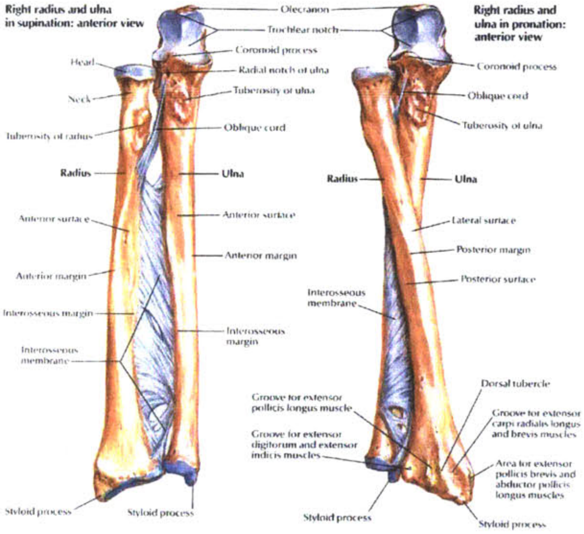

Figure 2-1: Bones of the forearm

Ulna: The proximal end of the ulna at the elbow joint is where the trochlear notch creates a fusion with the radial notch at the humero-ulnar joint. The front edge of the trochlear notch is formed by the coronoid process and the trailing edge is formed by the olecranon. The radial notch, which is positioned on the side and lower part of the coronoid process, receives the head of the radius. The distal end of the ulna at the wrist is conical and there is a portion that is gnarly known as the head, and a knob-shaped bulge which is the styloid process. This area is referred to as the distal radio-ulnar joint as it joins both the ulna and the radius.

Radius: The radius consists of a smaller proximal end and a larger distal end with a body between them. The radial chamber is quite obvious and designed for the attachment of the bicep muscle; it is positioned just below the head on the medial side. A double faceted surface at the distal end of the radius meets the proximal wrist bones. The styloid process of both the ulna and radius is designed for lateral and medial stability for the motion of the wrist.[23]

2.3.1 *Muscles and Tendons*

There are several muscles that are directly related to the bending of the arm, extension of the fingers and the moving of the hand up and down in the forearm. At the same time of course, there are nerves and arteries which support these movements. The system of muscles, nerves and arteries within the body is a complex one, so before referring to the muscles and nerves of the forearm, it is important to refer to the structure of skeletal muscle.[3]

2.3.2 *Composition and Structure of Skeletal Muscle*

There are over 600 muscles in the human body that combined, weigh in at about 2/5 of the entire weight of the body. The muscles are divided into three categories: skeletal, smooth and cardiac muscles, based on their structure, contractile properties and mechanisms of control. This work deals only with the skeletal muscles so they will be the only type analyzed below. [3]

The skeletal muscles adhere to bone and have the most significant contribution to the movement and support of the human skeleton. The expansion and contraction of skeletal muscle is mostly controlled by voluntary movement. In addition, through their movement, they are a heat source because they produce 85% of the total body heat[20]. The connection of skeletal muscle is accomplished by tendons and collagen fiber bundles, which are located at the ends of each muscle. To understand the power transfer from muscle to bone, it can be likened to a person (muscle) pulling a rope (tendon).

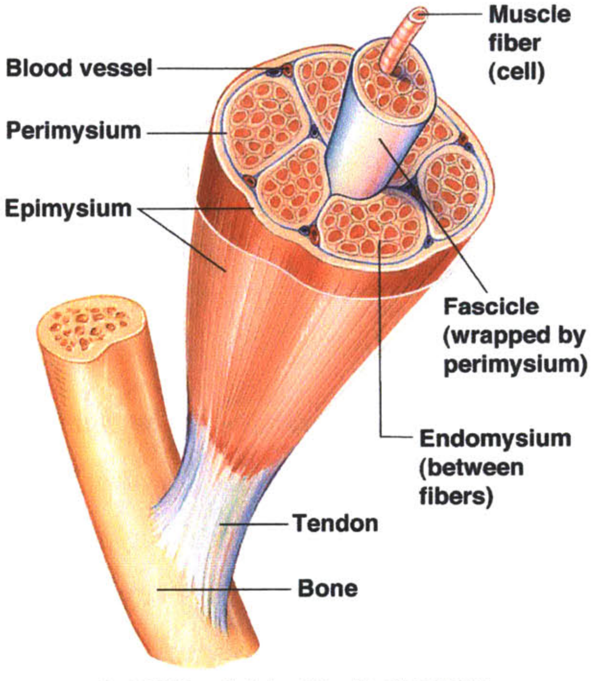

Figure 2-2: Basic components of a skeletal muscle

The basic unit by which the skeletal muscle is made of is referred to as a muscle bundle, made of elongated cells and muscle fibers. Each of these is a separate cell containing several hundred nuclei. The space between the muscle fibers is covered by connective tissue called endomysium. Furthermore, each muscle bundle is covered by a strong connective tissue, called perimysium. These bundles are then wrapped in an even stronger connective tissue which covers the muscle. This outer layer is called epimysium at its job is to surround, protect and distinguish the muscles. Figure 2-2 shows what has been mentioned in this paragraph.

The main function of the muscle fibers is the conversion of chemical energy to create motion and force. Their formation is completed at the time of birth and grows in size as the child develops, acquiring a diameter of 10-60 um and a length up to 30 cm long per muscle. The signals that the brain sends through the muscle fibers are what cause the muscle to either expand or contract. These are the signals that can be detected and read by the electromyograph, through which I have been recording and analyzing to better understand muscular movement.

2.3.3 *Structure and Organization of Muscle*

An understanding of the biomechanics of muscle function requires a knowledge of the gross anatomical structure and function of the musculotendinous unit and the basis of microscopic structure and chemical composition of the muscle fiber[3].

2.4 Background of Bio-Signal Processes

2.4.1 *Definition of Signal*

A signal is a function that conveys information about the behavior of a system or attributes of some phenomenon. A signal can occur naturally or be synthesized.[11]

Mathematically, a signal is expressed as the function of one or several independent variables, of which the most common are time and space:

$$t \rightarrow x\left(t\right) \tag{2.1}$$

A signal is not necessarily an electrical quantity, however, to perform activities such as recording, analyzing and modifying signals it is often convenient to utilize a signal in the form if an electrical quantity. With electrical systems, a wide variety of signal processing activities can be achieved. The challenge that arises is that we cannot easily extract the information we need from the signal as it contains the element of noise [11]. Determining how to reduce the impact of noise within the signal reading has been a challenge throughout my research process.

2.4.2 *Types of Signals*

A signal can be classified in different ways, as well as different categories. Depending on the purpose of use, the appropriate classification is chosen. This signals are divided based on their range of values.

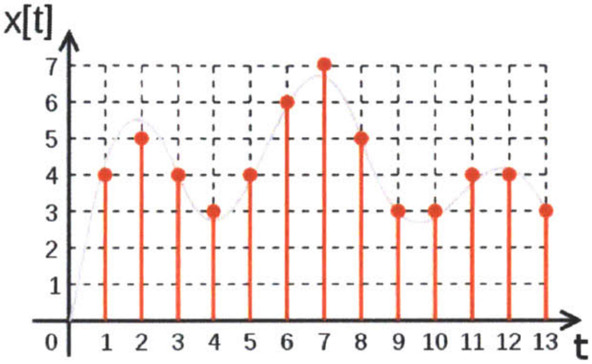

Figure 2-3: Analog and Digital Signal

Based on the dimensions, the signals are classified into:

1. One dimensional: They have only one independent variable, which is usually time. A common example is speech where time is the independent variable and acoustic pressure is the dependent [22]

2. Multidimensional: An example of a two-dimensional signal is an image where the spatial coordinates (x, y) are the independent variables and the dependent variable is brightness. An example of a three-dimensional signal is video, which is a sequence of images in time. Therefore, it differs to the image only in the independent variables, where now time is included, i.e. (x, y, t)

Based on a signal's description, it can be classified into:

1. Deterministic: Signals that can be described by a mathematical equation. In the real world, no signal belongs to this category as their form is affected by noise and unexpected changes in parameters. Nevertheless, it is quite convenient to try to model or approximate a signal with the help of deterministic functions. Periodic signals belong in this category.

2. Stochastic: Signals that cannot be expressed mathematically, but in terms of probability. In stationary stochastic processes, the dispersion of the random variables is the same for each value of the variable parameter. Therefore, they are processes whose statistics remain unchanged over time. In the real world, most signals are not static.[3]

2.4.3 *Definition of Biosignal*

Within the scope of biomedical signals and sensors, a biosignal can be defined as a description of a physiological phenomenon, irrespective of the nature of this description. Since there is nearly an unlimited number of physiological mechanisms of interest, the number of possible biosignals is very large[17]. In the broadest sense, the variety if biosignals extends from visual inspection of a person to signals recorded from the human body using sensors e.g., electrocardiography. The use of the stethoscope by a doctor for the heartbeat is a fairly simple example of recording biosignals. Of course, with the development of technology and advanced medical equipment, more opportinites to acquire and use biosignals are becoming available.

The largest number of biosignals are continuous-time signals. The most common process is their conversion into discrete through the technique of sampling. Those signals may be used to explain the physiological mechanisms that underlie a particular biological event or a system. Biosignals can be acquired in a variety of ways, depending on the type of biosignal and will be reported in the following section.

2.4.4 *Types of Biosignals*

The biosignals as simple signals can be classified in different ways and in many categories. Depending on the purpose of use, the appropriate classification can be chosen.

Based on the activation methods, signals can be classified into:

1. Active: The source for the measurement is derived from the patient himself ("internal source"). This category can be divided into two subcategories:

    (a) Electrical: Known as biopotential, it is the most widespread category of biosignals. Examples belonging to this type of signal are the signals generated by the body and recorded through the techniques of Electrocardiography, Electroencephalography, Electromyography, Electrogastrography etc.

    (b) Non-Electrical: Although it is common when we refer to biosignals to mean the bioelectrical signals, in fact there are also non-electric. Examples of this category are the body temperature and blood pressure.[14]

2. Passive: The energy source is outside of the patient (”external source”), for example an X-ray CT scanner.

2.4.5 *The Functionality of Electromyography*

An EMG sensor consists of two electrodes which are placed on a muscle in the orientation of its fibers; one is placed at the end of the muscle and one is placed at the middle or the ‘belly’. The sensor measures the voltage between these two electrodes, caused by nerve impulses. Even though a voltage difference is measured, nerve impulses are not delivered electrically, as a common misconception leads us to believe; they are caused through diffusion of Na+, K+ and Cl-” ions.[15][4] In the relaxed state, the interior of a nerve tract, also known as an axon, holds most negative ions while the positive ions are outside of the membrane. The potential inside a nerve cell in its relaxed state is -70mV . When a signal arrives through the axon, the local potential inside the cell starts to rise. As soon as it reaches -55mV, all positive ions from outside are forced inside the cell through ion carriers while the negative ions are forced out of the cell. The local potential inside the cell reaches a peak of +30mV. After that, the cell returns to its relaxed state.

At the very moment an EMG sensor measures a voltage difference, a signal is traveling along a nerve cell beneath the two electrodes. The force of contraction of a muscle is proportional to the number of muscle cells that are contracted simultaneously. Every muscle cell has its own nerve cell that controls it; if more nerve cells are sending signals simultaneously, the muscle contracts harder. The sensor sums up all the signals passing through all the nerve cells beneath its electrodes, therefore the amplitude of the measured signal is proportional to the force of contraction of the muscle.

There are two methods of recording the EMG signal with electrodes:

1. Intramuscular or Depth (needle fine-wire) Electrodes: Consists of a wholly insulated stainless steel needle with an exposed edge, as seen in Figure 2-4. It enters the inside of the muscle to record fine movements and activity within the muscle. The value of the signal resulting from moving beyond the muscle depends on the size of the electrodes and the distance between them. The size of the electrodes is determined by the diameter of the circular disk (1-3 cm) and it is important because it is proportional to the monitored muscular volume and inversely proportional to the resistance. Depending on the muscle you want to record, the proportionally sized electrode must be used. Before placement of the electrodes of this type, a specific skin preparation must be performed such as the removal of dead cells with light rubbing using rough material and cleaning with alcohol solution in order to reduce the resistance connection with skin electrodes.

Figure 2-4: Needle fine-wire electrodes for EMG recording.

2. Passive Surface Electrodes: Connected to an external amplifier circuit with the help of cables for proper signal acquisition, these consist of a metal disc, usually

silver or chlorargyrite (Ag or AgCl) or an adhesive disk, containing insulation everywhere except the point of contact with the skin. This type of electrode detects the average muscle activity on the surface and can be disposable or reusable.

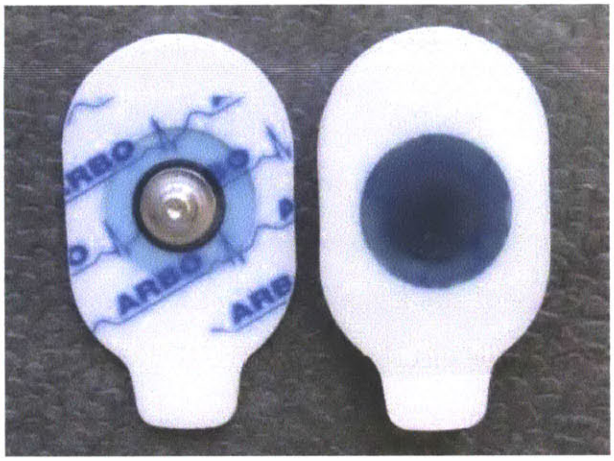

Figure 2-5: Surface electrodes for EMG/ECG recordings.

3. Active Surface Electrodes [45]: These electrodes have an attachment containing a pre-amplification for surface electrodes and are commonly referred to as dry electrodes because there is no demanding preparation of the skin surface needed in the area where we want to measure. In fact, the high input impedance of the amplifier is placed close enough so an electrolyte cream is not even needed.

The basic difference between surface and depth electrodes lies in the frequency range. Assuming that the signal recorded by needle electrodes do not pass through the skin and fat tissue that act as a low pass filter, they have a much higher frequency range, i.e., up to 5000 Hz, in contrast to that of 500 Hz of surface electrodes. Of course, the placement of the intramuscular electrodes is a much more painful process to the patient than the placement of the surface electrodes, although the type of electrode that is needed is ultimately dependent on the case.

In each case, the electrode is either monopolar or bipolar:

1. An electrode of monopolar configuration is placed over the belly of the muscle, with an electrode placed further away used as a reference, and the signal

generated between both electrodes is amplified and recorded.

2. In the case of bipolar electrode configuration, two recording electrodes are placed over the belly of the muscle within 1 to 2 cm of each other, putting a reference electrode further away but equidistant from the two recording electrodes. The signal generated in the recording electrodes is subtracted one from the other and the output signal relative to the reference is amplified and recorded. The bipolar electrode configuration has the advantage that it removes the common noise between the two electrodes and thus the signal obtained has less noise overall.

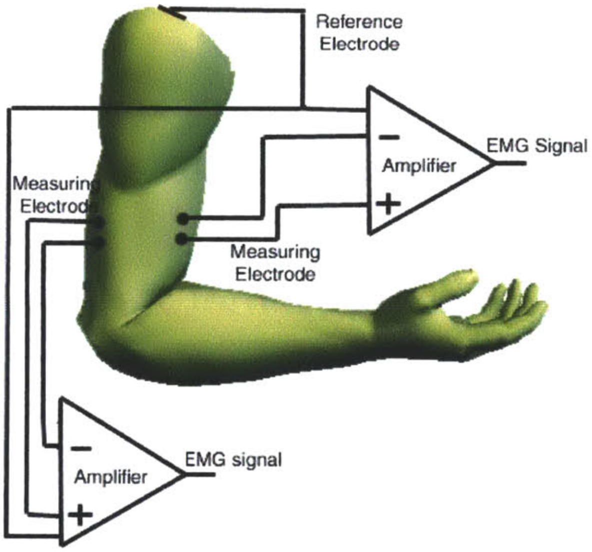

Figure 2-6: Surface electrodes for EMG diagram.

When the muscle is relaxed, a more or less noise-free EMG baseline can be seen. The raw EMG baseline noise depends on many factors, especially the quality of the EMG amplifier, the environment noise and the quality of the given detection condition. Assuming a state-of-the-art amplifier performance and proper skin preparation, the averaged baseline noise should not be higher than 3-5 micro-volts. The investigation of the EMG baseline quality is a very important checkpoint of every EMG measurement.

By its nature, raw EMG spikes are of random shape, which means one raw recording burst cannot be precisely reproduced in exact shape. This is due to the fact that the actual set of recruited motor units constantly changes within the matrix of available motor units: If occasionally two or more motor units fire at the same time and they are located near electrodes, they produce a strong superposition spike. By applying a smoothing algorithm or selecting a proper amplitude parameter, the non-reproducible contents of the signal is eliminated or at least minimized.[19]

The EMG signal is useful because we can study:

1. The functional role of muscles, ie, we can learn what muscles are of primary motion for a particular movement.
2. The simultaneous activation of agonist and antagonist muscles.
3. Muscle fatigue and its role in the functional role of the forearm.

2.5 Principles of sensory motors

People show a remarkable capacity to learn a variety of motor skills, ranging from tying shoe-laces to trying to get a basketball through a hoop. The process of learning such skills requires a number of interacting elements; the first being to efficiently gather task-relevant sensory information, decision making and selection strategies, along with the implementation of both predictive and reactive control mechanisms.[36]. Second, there are different learning processes that apply to these components, which each specifying how errors and rewards drive learning. at last, learning is strongly determined by a neural representation of motor memory[1].

This thesis explores the multiple streams of sensory information, within and across modalities, to be specific, visuo-haptic integration. This integration is optimal even when it comes from a hand-held tool[2]

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[1] Motor memory is the ability to remember specific motor movements, such as dance moves and then replicate them.

[2] Visuo-haptic integration is the process that combines visual information and haptic information into a single perception[36]

Sensory motor streams are temporally delayed and tend to be corrupted by appreciable amount of noise. There are at least three computations that can improve the accuracy of the sensory information and that can be very relevant for understanding and informing the development of systems that augment or improve the motor learning itself.

1. Error-based learning: Every time we make a movement, our sensorimotor system senses the movements outcome and compares this to the desired or predicted outcome. The information contained in such sensory prediction errors not only tells the system that it missed the goal but also specifies the particular way in which the target was missed. To be able to use this information, the nervous system needs to estimate the gradient of the error with respect to each component of the motor command that is, whether the error will go up or down as a component is increased or decreased.

2. Use-dependent learning: The term use-dependent learning has been used in references to the phenomenon that the state of the motor system can change through the pure repetition of movements, even if no outcome information is available.

3. Reinforcement learning : There are situations in which error-based learning cant easily be applied (for example, learning the movements to make a swing go higher) because the goal and the outcome are far removed from the action. In this situation, reinforcement learning techniques can be used to assign credit or blame to the events that lead to the success or failure[11]. The reinforcement learning model presents promising qualities to helps us improve the time it takes to learn a task during the early stages of learning a craft.

2.6 Sensory Substitution vs. Sensory Augmentation

Sensory substitution was developed and mainly used to help people with one or multiple modal impairments to achieve a better quality of life [1]. This was done by augmenting other modalities to make up for the lost one. It was first conceived by neuroscientist Paul Bach-y-Rita, who proved the brains capacity to transform itself by enhancing certain areas when one or several modalities were injured. Since then there have been a series of developments in the medical field and in the arts world that deal with these explorations. In this chapter, some of the projects that represent the ideas proposed in this thesis are introduced.

Figure 2-7: Early sensory substitution experiments by Paul Bach- y-Rita

2.6.1 Visual Augmentation

There are cases where people with certain eye disorders see better with higher- or lower-than-normal light levels; an illuminance from 100 to 4000 lux may induce comfortable reading [6]. Ideal illumination is diffuse and directed from the side at a 45-degree angle to prevent glare. The surrounding room is preferably 20"%" to 50"%" darker than the object of interest[16].

An object that normally gets overlooked as an augmentation device are the eye glasses. Refractive errors cause difficulties in focusing on an object at a given distance from the eye [35]. Myopia (near-sightedness), hyperopia (far-sightedness), astigmatism (focus depth that varies with radial orientation), and presbyopia (loss of ability to adjust focus, manifested as far-sighted- ness) are the most common vision defects. These normally can be corrected with appropriate eyeglasses or contact lenses and are rarely the cause of a disability.

Magnification is the most useful form of image processing for vision defects that do not respond to refractive correction. The simplest form of image magnification is getting closer; halving the distance to an object doubles its size. Magnifications up to 20 times are possible with minimal loss of field of view. At very close range, eyeglasses or a loupe may be required to maintain focus[6]. Hand or stand magnifiers held 18 to 40 cm (not critical) from the eye create a virtual image that increases rapidly in size as the object-to-lens distance approaches the focal length of the lens. Lenses are rated in diopters ($D = 1/f$, where f is the focal length of the lens in centimeters). The useful range is approximately 4 to 20 D; more powerful lenses are generally held close to the eye as a loupe, as just mentioned, to enhance field of view. For distance viewing, magnification of 2 to 10 times can be achieved with hand-held telescopes at the expense of a reduced field of view.

2.6.2 Visual Substitution

With sufficient training, people without useful vision can acquire sufficient information via the tactile sense for many activities of daily living, such as walking independently and reading. The traditional long cane, for example, allows navigation by transmitting surface profile, roughness, and elasticity to the hand. Interestingly, these features are perceived to originate at the tip of the cane, not the hand where they are 2000 by CRC Press LLC transduced; this is a simple example of distal attribution[7]. Simple electronic aids such as the hand-held Mowat sonar sensor provide a tactile indication of range to the nearest object. Braille reading material substitutes raised-dot patterns on 2.3-mm centers for visual letters, enabling reading rates up to 30 to 40 words per minute (wpm). Contracted Braille uses symbols for common words and affixes, enabling reading at up to 200 wpm (125 wpm is more typical).

More sophisticated instrumentation also capitalizes on the spatial capabilities of the tactile sense. The Optacon (Figure 2-8)(optical-to-tactile converter) by TeleSensory, Inc. (Mountain View, Calif.) converts the outline of printed letters recorded by a small, hand-held camera to enlarged vibrotactile letter outlines on the users fingerpad. The cameras field of view is divided into 100 or 144 pixels (depending on the model), and the reflected light intensity at each pixel determines whether a corresponding vibrating pin on the fingertip is active or not. Ordinary printed text can be read at 28 (typical) or 90 (exceptional) wpm. Spatial orientation and recognition of objects beyond the reach of a hand or long cane are the objective of experimental systems that convert an image from a television-type camera to a matrix of electrotactile or vibrotactile stimulators on the abdomen, forehead, or fingertip.

With training, the user can interpret the patterns of tingling or buzzing pints to identify simple, high-contrast objects in front of the camera, as well as experience visual phenomena such as looming, perspective, parallax, and distal attribution [1] Access to graphic or spatial information that cannot be converted into text is virtually impossible for blind computer users. Several prototype devices have been built to display computer graphics to the fingers via vibrating or stationary pins. A

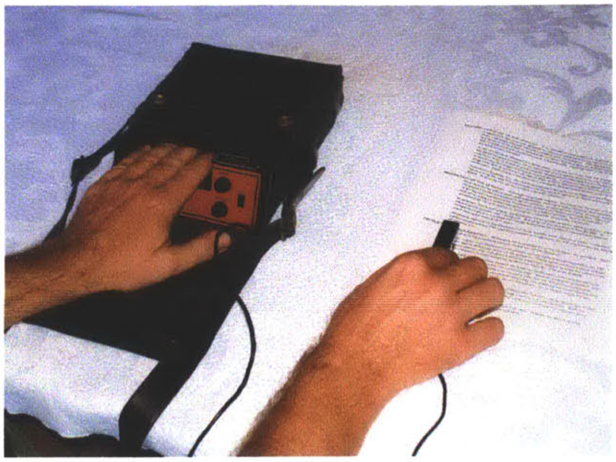

Figure 2-8: Image of Optacon instrument by Telesensory

fingertip-scanned display tablet with embedded electrodes, under development in our laboratory[2], eliminates all moving parts; ongoing tests will determine if the spatial performance and reliability are adequate.

Chapter 3

Explorations

3.1 Motivation for Hardware Development

The previous chapter presented the background of this thesis in three parts with a physiological overview of human skeletal muscle anatomy, a brief historical review of sensory augmentation and an introduction into the bio-signal subject and how to acquire such a signal and a discussion of motor skill processes. In this chapter I describe the experimental approach and apparatus utilized for the proposed bio-feedback experiments. The focus is to describe the apparatus (hardware components, integration and real-time software implementation) as well as some of the experiments that are possible under the system architecture. For illustration purposes, experimental measurements comparing single muscle workloops under zero and non-zero admittance loads are presented. In doing so, methods for conducting experiments on controlled and uncontrolled environments are presented.

3.1.1 *Components of the Device*

1. A compression sleeve is fitted over the arm of the participant, from shoulder to wrist on the dominant hand. The sleeve features small patches of conductive fabric that are placed strategically over the general areas of the bicep, wrist flexors and forearm flexors. These patches have snap connections that allow the

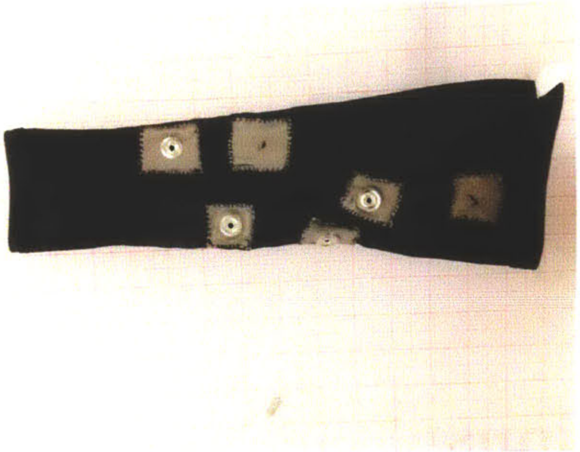

Figure 3-1: Comprassion sleeve with conductive fabric patches and fabric snaps.

electrodes to snap onto the sleeve while maintaining a conductive connection.

2. The electrodes connect back to the EMG Band located at the top of the bicep near the shoulder joint. The EMG Band slides over the sleeve and tightens down with a simple flexible fabric band, similar to an armband used to secure an MP3 player to the arm while jogging. This is where the program is loaded and the computation occurs using a Teensy microcontroller.

3. Participants can easily visualize their actions through the Visual Display, located at the wrist on a strap made of 3D printed flexible plastic material. The strap has three narrow slots that strips of LEDs have been concealed within, allowing them to be visible to the participant when they are illuminated.

3.1.2 *Design of EMG Circuit*

Most EMG signals have a frequency content ranging from 0 to 500 Hz, with dominant energy between 50 to 150 Hz. However, content at up to 2000 Hz may be useful. The amplitude of the signal may vary from less than 50 μV up to 30 mV (Clancy et al., 2002). The nature of EMG signals and various EMG equipment properties determine the quality of a recording. Besides motor units (muscle cell group) and electrode characteristics, there are other factors that distort and add undesirable noise to the

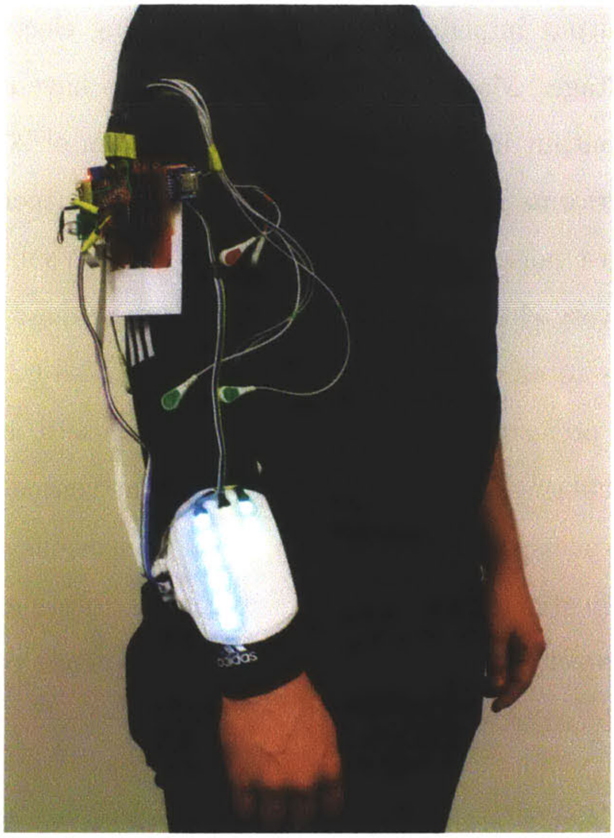

Figure 3-2: Image of all three components as worn by a participant.

signal. A DC offset due to half-cell potentials within the tissues can be as high as 300 mV. Muscle crosstalk (signals from motor units of neighboring muscles) may result in misleading information about the investigated muscle. Ambient 60 Hz noise from power supplies may result in power line noise. Inherent noise generated by electronic equipment can range from zero to thousands of Hz. Motion artifacts due to electrode or cable movement add noise to the EMG signal in the frequency range of 1 to 5 Hz [5]

Typically, EMG is acquired in two stages. The first (electrodeamplifier) stage includes signal transduction/detection and preamplification. This stage is placed as close to the skin as possible, generally with the electrodes and the electronic amplification arranged within a single package. The second (signal conditioner) stage provides further signal conditioning. The electrodeamplifier has a high input impedance to limit current drawn from the subject and therefore minimizes signal distortion and attenuation. Low output impedance drives the following electronic stage without change in output voltage. Modern operational amplifiers have an input impedance of over 100MΩ and output impedance under 100 . A gain of 20 is implemented to improve electronic performance within the electrodeamplifier (increase common mode rejection ratio, decrease noise) and decrease inherent noise in subsequent stages. The amplifier is situated very close the electrodes, insuring the most precise information about the EMG prior to amplification and diminishing noise from cable movement. This configuration is preferred by many researchers because it attenuates noise and motion artifact by buffering the acquired signal near the source and amplifying the signal early in the process; and minimizes physical dimensions of a device by only including a preamplification stage near the subject. To prevent hazardous current from entering the subject, the power supply of all components on the subject's side of the circuitry is isolated from earth ground.

(Upon the completion of the research), three major electromyograph circuits based on open source designs were created. All of the designs approaches to the problem were essentially very similar as their initial and final stages included the same type of filtering and were storing collected data on a personal computer. The main differences between the designs included approaches to signal amplification and digitization.

One of the contributions that was my intent from the start was a Fab-able [8][1]EMG board; a low cost device that anyone could build for under 20 dollars. This goal created a lot of challenges due to nature of the signals and the fabrication methods chosen from the start.

3.1.3 *Sensor Placement*

There are three main muscles that I looked at when researching the forearm; the bicep, wrist flexors, and forearm flexors. Each of these muscles become active during the process of creating through ceramics, however the research was not limited to

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[1] Fab-able: Term used to describe objects created with the Fab lab equipment and Fab Modules software

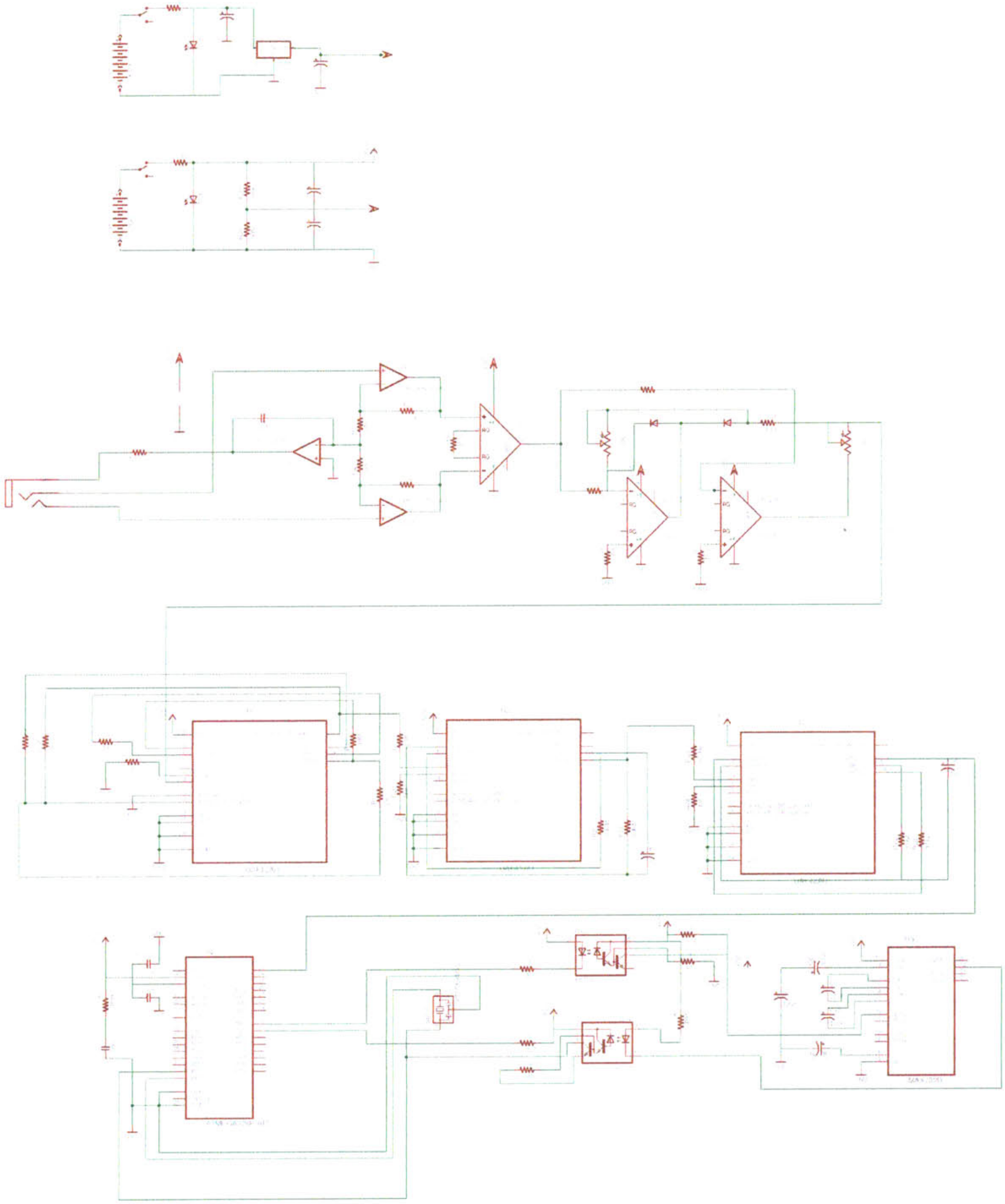

Figure 3-3: Circuit used during the prototyping stages.

targeting these muscles. During some of the collection data experiments other muscles near or related to an action where recorded. Some of these muscles are the pectorals, major and gastrocnemius muscle. These additional muscles were recorded using stick on electrodes for studying purposes but not implemented into the final experiment.

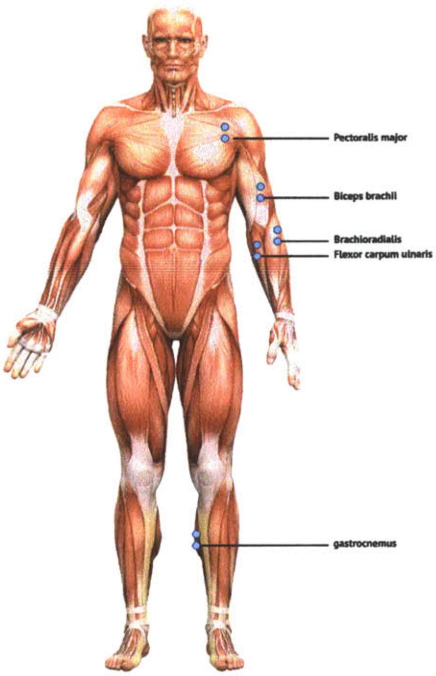

Figure 3-4: Targeted muscles.

When utilizing the stick on electrodes, pairs of electrodes were placed on the muscles, one at the center or the belly of the muscle, and one towards one end. The EMG takes readings at both locations and averages the current between them to determine how much force the muscle is exerting.

3.1.4 *Adapting the Sensors to the Microcontroller*

The EMG sensors had to be adapted to work with the Teensy 32 bit ARM microcontroller[13]. Teensy can only read input values between 0V and 3.3V, whereas the sensors produced output values above 5.0V. The level of amplification of the signal can be adjusted over a potentiometer on the circuit board of the sensor ranging from 0 to 5k.

In order to change the signal range from [−3.3V, 3.3V] to [0V, 3.3V], an offset voltage of 2.5V was added to each signal. I tested many different amplifier levels and smoothing algorithms and utilized only the most successful on the participants.

3.2 Conversion of Analog Signal to Digital

Analog signal contains an infinite amount of information, unlike the discrete which contains a certain amount of information and is a subset of a corresponding analog data set. Of course, because many signals generally in nature and more specifically biological signals are analog, it is needed to convert them to digital signals in the form of a sequence of numbers of finite precision to achieve easy processing. This process is called analog to digital conversion. To create a discrete signal from an analog, an analog-to-digital converter (A/D) is needed with sampling period T_s. It should be noted here that a discrete signal can come from many different analog signals and be identical in all cases. The only change is the frequency or sampling rate that is denoted f_s which is $f_s = 1T_s$ [26].

3.3 Sampling Techniques

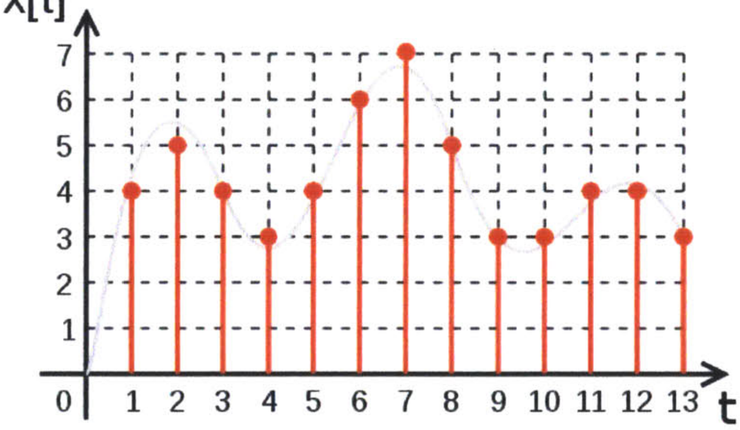

Figure 3-5: sampled signal.

The other important technical item is the selection of a proper Sampling Frequency. In order to accurately translate the complete frequency spectrum of a signal, the sampling rate at which the A/D translation in the Teensy provides the 16-bit ADC that samples close to 30 thousand samples per second. Knowing this, we can then determine that the voltage of the input signal must be at least twice as high as the maximum expected frequency of the signal. This relationship is described by the Sampling Theorem of Nyquist: sampling a signal at a frequency which is too low results in aliasing effects. For EMG almost all of the signal power is located between 10 and 250 Hz and scientific recommendations (SENIAM, ISEK) require an amplifier band setting of 10 to 500 Hz. This would result in a sampling frequency of at least 1000 Hz (double band of EMG) or even 1500 Hz to avoid signal loss. The code used to collect the data was set to match these specs, however since a microcontroller is a single thread processor, the time in which a data sampling function is performed drops in order to do other functions. For the purpose of this study those variations didn't seem to impact the end result, but it was important to keep track of the time a function takes to run. In order to classify the signals measured with the EMG setup, we first performed some basic signal processing to transform the time series data into a time- independent data set. This is done by using the Olimex ECG/EMG Arduino shield[12]. The values of the feature vector are normalized based on a four-second calibration step where users sequentially pinch each of their fingers.[19]

3.4 Visual Feedback

The primary goal is to provide a supervised input to the person learning a task to prove that biofeedback signal representation is a suitable method in the context of learning. This assumption is based on the work done by a team at the Laboratory of Motor Control, Research Center for Motor Control and Neuroplasticity, Group Biomedical Sciences[27]. During the past few decades, they have demonstrated that providing augmented visual feedback also facilitates the learning of bimanual coordination patterns [21][10][33][34], giving rise to complex multi-sensory integration mechanisms [29].

Figure 3-6 diagrams the flow in which the user gains information from the master craftsman; the user is able to receive both audio and visual feedback as they would in any other learning environment, but they have the added knowledge of EMG data and kinetic motion as it is processed through the sensors and translated into an LED

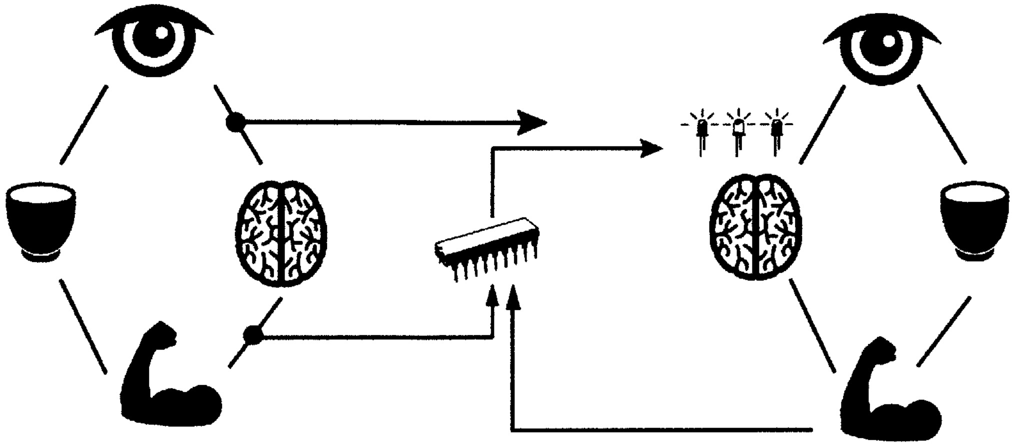

Figure 3-6: The diagram above is a representation of the flow in which this thesis envisons biofeedback.

visual display. This new information is joined with the audio/visual information to create a reinforced feedback loop that generates an accelerated learning environment.

The current visual display used in this thesis, as limited as it might be at the current state, is capable of providing visual indicators via color change and an increase in illuminated pixels as a reward system or decrease of illuminated pixels to assign blame. A limitation of the setup is that the subject has to be able to see the information recorded and loaded into the system in order to comprehend the control set of movements. Currently the system does not inform the user as to the direction in which he or she is to move in order to replicate the motions of the master craftsmen; for example, the visual display can communicate that the forearm must be perpendicular to the upper arm, but it does not inform the user whether the arm has to be parallel to the ground or 90 degrees pointing towards the sky. In order for the user to replicate the motions in a timely manner, he or she must witness the original technique set forth by the master craftsman. Otherwise the user would be forced to replicate every possible movement before the visual display would produce a positive result.

The first of the LED strips, closest to the thumb, measures both the position of the forearm as well as the angular velocity when performing the task. The number of lit LEDs increase with proper movement, as well as a change in color to show progress. The LED starts with a red light and progresses to magenta, blue, yellow, and green to show mastery of the skill. This is achieved by processing information from the 9dof sensor,[2] and using Sparkfun's C++ library allowing the heading, pitch and roll[3] of the arm to be calculated. The data output from the sensors are in degrees and by having this information, one can begin to compare how close or how far in degrees a movement or arm position is in comparison to the control data. The boolean result from those comparisons are then passed into the visual display.

The middle strip of LEDs measure the EMG signals produced by your body during the task. These lights also increase in quantity and color to denote progress, but this time changing from yellow, to orange, to red to show improvement. Similarly to the angular position mentioned above. The middle strip takes the data from the filtered signal and looks for matches in the amplitude of the signal between the student and the master. The signal is filtered with a low pass filter[4] and a peak detector envelop filter[5], this provides a more useful signal with the right information of the muscular activity.

The final strip of LEDs at the pinky side of the display compares the current position and EMG signals of your forearm to that of the control data. This strip operates slightly different than the other two in that the lights do not progress but

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[2] This is the LSM9DS0, a versatile motion-sensing system-in-a-chip that houses a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer sold by sparkfun.

[3] Yaw, pitch and roll is a way of describing the rotation of the camera in 3D. There is other ways like quaternions but this is the simplest. Yaw, pitch and roll is the name of how much we should rotate around each axis

[4] A low-pass filter is a filter that passes low-frequency signals and attenuates (reduces the amplitude of) signals with frequencies higher than the cutoff frequency. The actual amount of attenuation for each frequency varies depending on specific filter design.

[5] The signal's envelope is equivalent to its outline and an envelope detector connects all the peaks in this signal.

instead, they will remain green when the participant is working 'correctly' and will turn red when the participant is not.

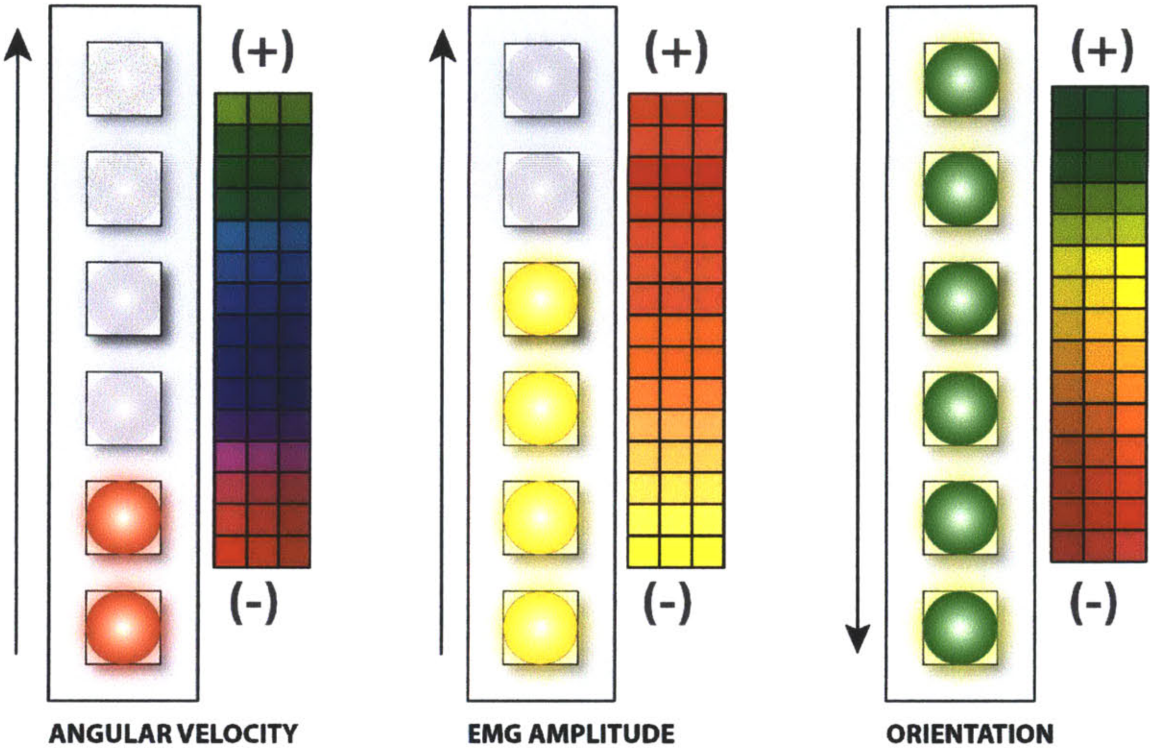


Figure 3-7: LED color chart.

Chapter 4

Experiments

4.1 Experiment Overview

The basis of my experiment is to record how a master craftsman performs a particular task in the field of ceramics, and then compare how closely a student can replicate the master's force, position and speed. By comparing how the student performs in relation to the master, he or she will be able to determine how they need to alter their motions to more closely resemble the master's technique.

In order to accurately record the data of both the master craftsmen as well as the apprentices, I have created a controlled environment suited for work with clay. This space has been set up with video equipment throughout the room in order to record important motion-tracking information which will then be digitized and converted into visual simulations.

4.1.1 *Procedure*

The series of events that were described to the participants are as follows:

1. Tracking markers will be placed on your body, which will allow me to track your motion using videography.
2. Adhesive electrodes will be placed in a few areas on both your forearm, elbow,

and bicep. There will always be pairs of electrodes; one at the middle or the belly of the muscle, and one towards an end.

3. For the first trial, you will perform the assigned task on two pounds of clay.
4. Once all the components are on and working, you will begin to work on the pottery wheel for five minute intervals, for up to twenty minutes in total.
5. For the second trial, you will perform the assigned task on five pounds of clay.
6. Again, you will work with the clay for five minute intervals, for up to twenty minutes in total.
7. After you have completed both trials, I will ask you to carefully remove the components and return them to me. You will then be able to wash yourself of any splashes of clay and exit.

4.2 Experiment Control Group

In order to test the system developed in this thesis, it was crucial to set a control group. By being able to compare data collected with the system prototyped for this study from a state of the art facility, one can begin to gauge results. Conducting the initial experiment in an ideal environment allows me to record data with the lowest level of noise possible, which will then give me a datum to which all other experiments can be compared to.

4.2.1 *Vicon / Delsys wireless system*

A 3D motion-capture system was used to record full or partial body movement. Multiple reflective markers were placed on subjects to identify body segments and joint-points thought to be anatomically significant for human movements. The movements of these markers resulted in trajectories recorded in 3D computer space. Once captured, trajectories could be displayed and other information such as computer-generated musculoskeletal models to represent the human subjects could be added. (Fig. 4-1)

A nine-camera VICON v8i motion-capture system [12] was employed to track markers (9 mm in diameter) at a rate of 120 frames/second. Marker tracking was accurate within 1.5 mm. We placed markers on subjects as follows: four on the head, left and right shoulder, one marker on the center of the clavicle, the C7 area of the spine, right scapula, left and right elbow mid and ulna, left and right upper arm, left and right lateral side of forearm, left and right radius and ulna, left and right thumb, left and right middle finger.

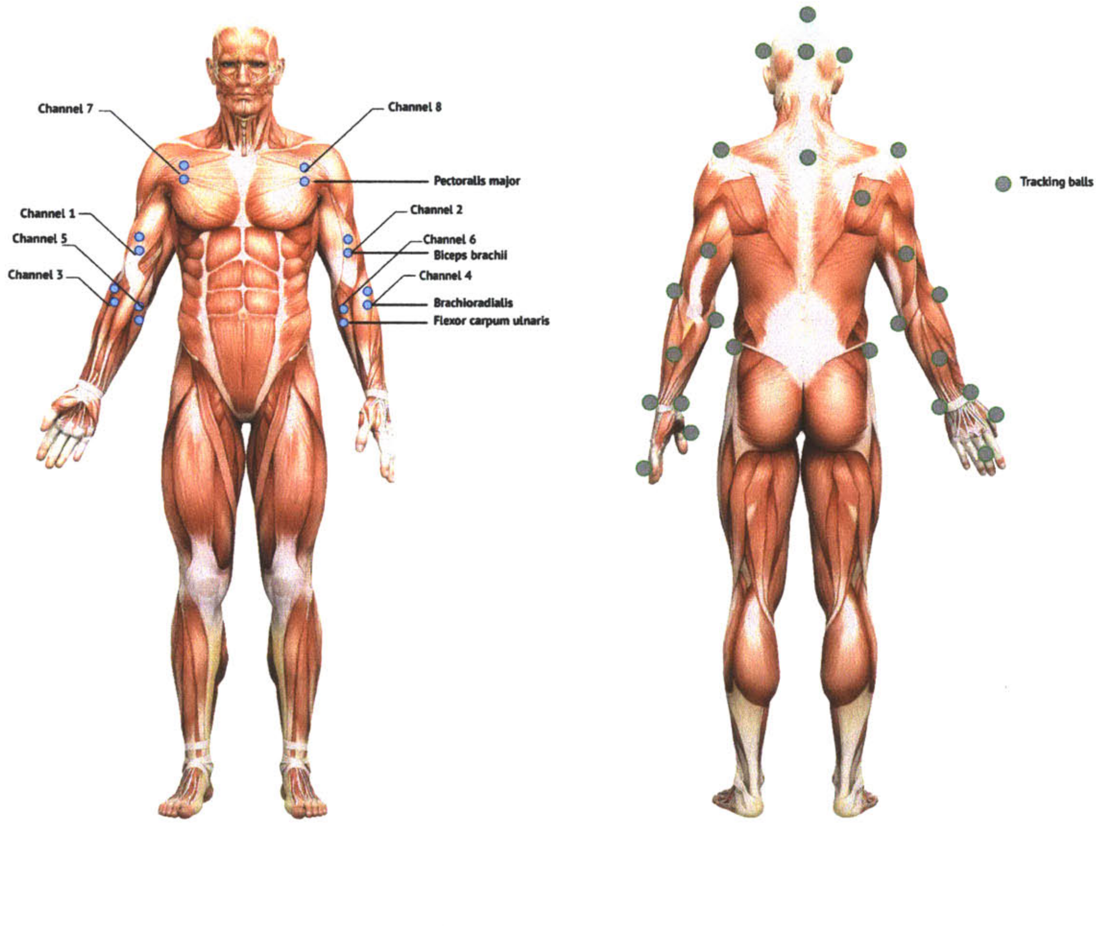


Figure 4-1: Location placement for the tracking balls and Delsys EMG system.

4.2.2 Trial Setup

The Vicon System is capable of connecting analog and digital devices to its mainframe, the same way a computer can connect to a wireless mouse. This versatile system provides continuous storage capabilities for 16 Trigno sensors (Delsys's EMG wireless system) operating at a full bandwidth with 3 DOF accelerometer data per sensor.

Once all sensors are placed on the body, the subject then can move into the space where the group of calibrated infrared cameras are ready to start collecting data.

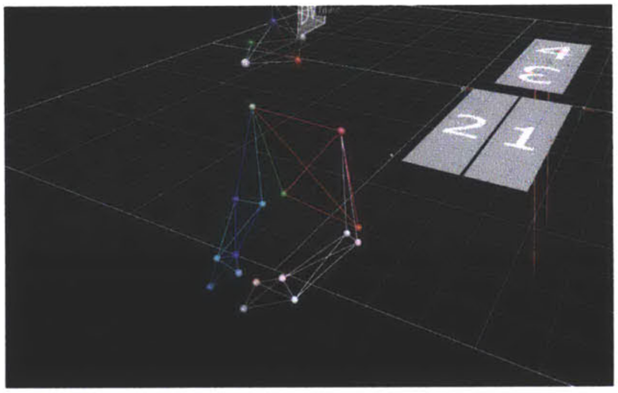


Figure 4-2: Reconstructed real time 3D wireframe model

The first subject was a pottery instructor with over 10 years of experience working with a pottery wheel. In order to collect data that was consistent, the instructor was asked to perform the initial actions when working on the wheel for longer periods of time in order to identify specific patterns for later use. A total of four recordings were collected producing an interesting result of the translation to the digital space of materiality. By tracking the motions of the hands while working with clay [Figure 4-2] a translation of materiality gets embedded into the 3D data.

In order to obtain the other end of the control group, Subject02 was someone with no pottery experience or any hand making background. Subject02 received a demo as if she was taking an introductory course to pottery. The demo took about 25 minutes for sake of clarity into the main aspects that this thesis is focusing; an emphasis was placed on centering the clay to the center of the wheel and coning the clay up and down. The subject was also shown how to create a hole in the center

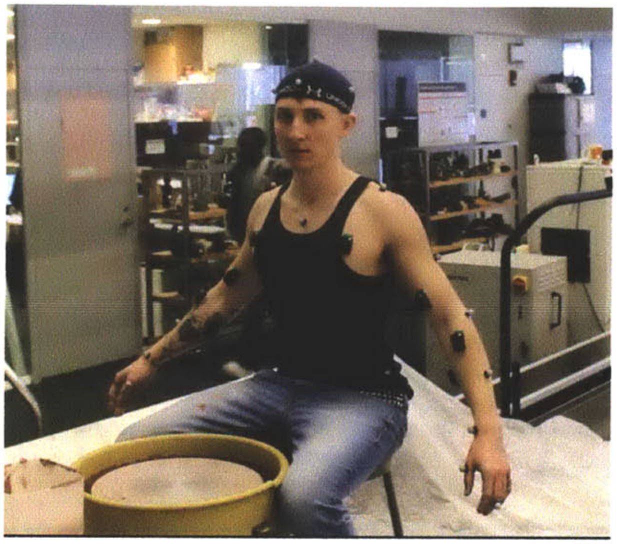


Figure 4-3: Subject01 in a controlled environment with sensors on the body.

of the clay, opening the hole and finally create a cylinder. The instructor provided explicit information as to what he did during the demo and pointed out key actions to pay close attention to. During the experiment the instructor also provided verbal instructions to try to help Subject02.

Figure 4-4: Subject01 teaching Subject02 how to work with clay while Subject02 wears motion sensors.

Image 4-5 shows the representation model of the two subjects while working on the wheel. The EMG data is shown as a series of plotted graphs. Each graph represents a channel, and the length of the plot is related to the the duration of the recording.

As one might guess, there is a difference between the EMG signal of the master and that of the beginner. These signals clearly show the contrast between the moment of muscular contraction and muscular extension. The EMG signals collected from the master show burst only in at intended times, while the beginner's signals are in a constant oscillation due to the nervous nature of the beginner and the lack of knowledge of the technique.

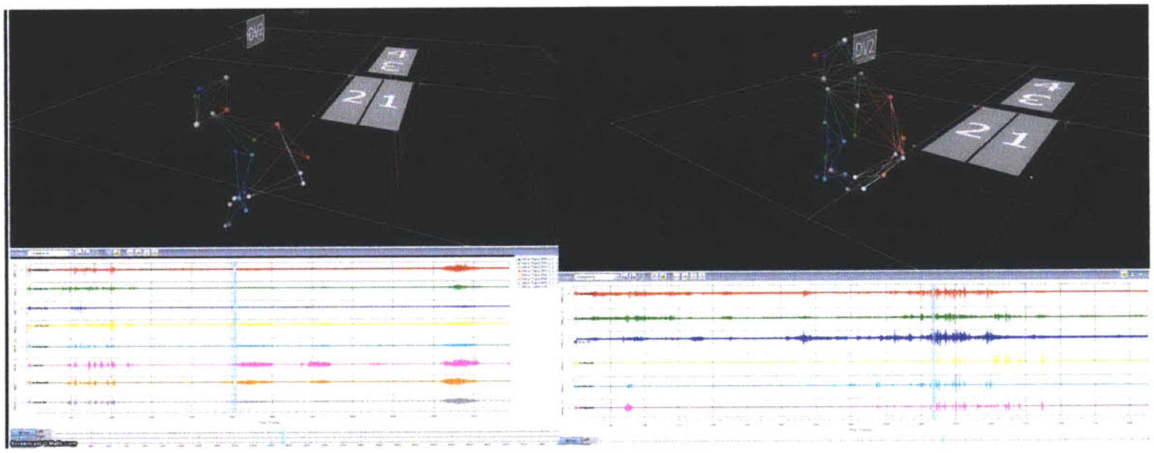


Figure 4-5: Comparison of master EMG signals to that of the beginner.

4.3 EMG Sleeve Initial Tests

Some subjects will have no visual feedback from LEDS and will have to rely on the indications from the instructor to perform. Others will wear the components while performing the task and I will later compare the two different sets of data. All participants will be recorded in order for me to track the motions using the sensors placed on their body. The ability to track the participants' motions will allow me to compare that of the participants using the device to those who were not using the device, giving me the opportunity to determine if the visual feedback makes an impact on the user's technique.

4.3.1 *Test 1 - Evaluating Sensitivity of Sensors*

The first test I conducted using the devices consisted of a simple movement, which the subject performed and then had to match to evaluate the accuracy of the sensor readings. For this test, I had the subject wear only the Visual Display so I could isolate the sensors measuring the position of the arm over a span of time, thus producing a speed and trajectory of the arm's movements. This information is displayed through the first row of LEDs on the visual display, so I disregarded any EMG data for this test.

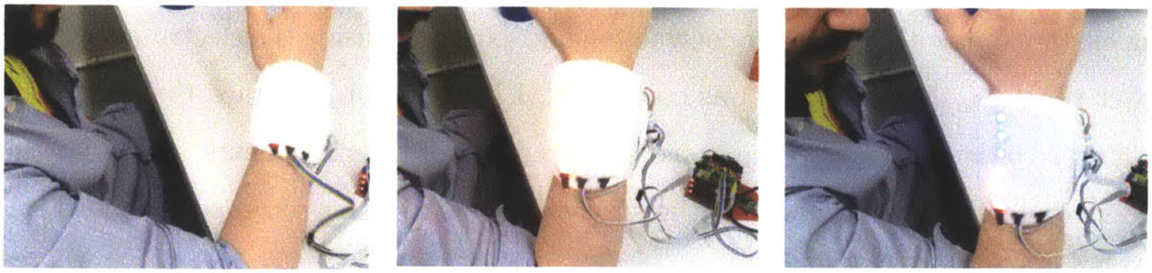


Figure 4-6: Evaluating Sensitivity of Sensors.

I asked the test subject to perform the same motion a single time to compare their motions to the previous test run. We had to perform multiple test runs because the subject could not easily match the control set of data. When the subject thought they were reproducing the same motion, the LED display showed a different evaluation of the movement. It took time and effort for the subject to slow their motions and focus on the display to determine how he needed to adjust his arm to match the previous test. After a few trials I determined that increasing the threshold of accuracy gave the subject more leniency in their motion, producing a positive result.

4.3.2 *Test 2 - Evaluating System Efficiency*

For my second preliminary test, I had the subject wear all three components so I could test all aspects of the device. I had the subject perform a few different experiments in order to test the posture and force the subject applied to the test material.

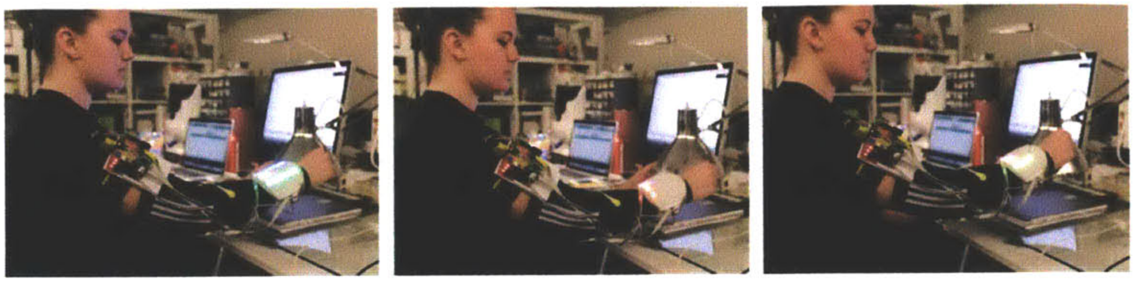


Figure 4-7: Tracing the outline of a lamp.

For the first experiment, I had the subject crush a paper cup using her hand, allowing me to monitor the muscular contraction and expansion using the electromyograph. After the paper cup crushing was completed, I had the subject trace the outline of a lamp in order to monitor the speed and accuracy of her movements over time. In order to monitor the accuracy of the subject's motion, I first recorded a control set which she then tried to match.

4.3.3 *Test 3 - Evaluating System while working with clay*

For the third and final test, the subject wore all three components so I could test all aspects of the device. I had the subject perform some of the first motions that are done when working with clay, namely the task of centering the clay on the pottery wheel. After seeing the demonstration from the instructor, the subject was asked to repeat the motions and to try to center the clay using only the device. The instructor was present to intervene when necessary but it was the goal for the subject to complete the task by solely relying on the information made available to him through the visual display.

After allowing the subject to take the time he needed to complete the task successfully, it was clear that the thresholds of the program were far too strict; the subject could not fully replicate the instructor's movements without having to restart and move very slowly. In order to calibrate the system so that the signals matched, the parameters on the program had to be adjusted and the thresholds had to be increased in order to allow the user to adapt and understand how the system works. The angular velocity threshold changed from 2 to 6, and the EMG reading threshold increased by 10.

It was obvious that the subject was centering the clay much faster than those that did not receive any feedback; his technique was not perfect, but the subject could complete the task in a shorter time frame and more successfully than those without feedback. The subject was successful and efficient with his right hand due to the fact that he had a constant feedback loop through which he could adjust his movements, however he was unclear as to how to use his left hand due to the fact that he had no feedback on that arm's movements. This was a clear manifestation of the error based learning principle as he adjusted his left hand many times to find a useful position. One can wonder how successful the subject might be if he had devices on each arm providing him with twice as much feedback?

Figure 4-8: Subject03 using visual feedback to guide his arm movements.

Figure 4-9: Subject03 using visual feedback centered clay.

Chapter 5

Experiment Findings

5.1 Results and Feedback

I found through preliminary experiments that is is very easy for the participant to become familiar with the movements of the task at hand without paying close attention to the visual display. The participant felt as though they were performing the task correctly, when the display was reading a different result. Once the participant re-focused on the output of the visual display, they were able to adjust their technique to meet the readings of the control data set.

Figure 5-1 depicts the range in which the EMG data is considered a match to the master craftsman; the pink data from the expert and the blue data from the novice, although they are differing, would be considered a match with the adjusted threshold settings. Throughout the learning process, one can reduce the positive match area to increase the level of difficulty in producing movements that match the master craftsman. The same process occurs with the data collected from the motion tracking sensors.

During the development of the code and the programming of the feedback display, I also found that the final strip of LEDs on the pinky side of the wrist performed extremely well in monitoring the position of the forearm. It was very clear to the

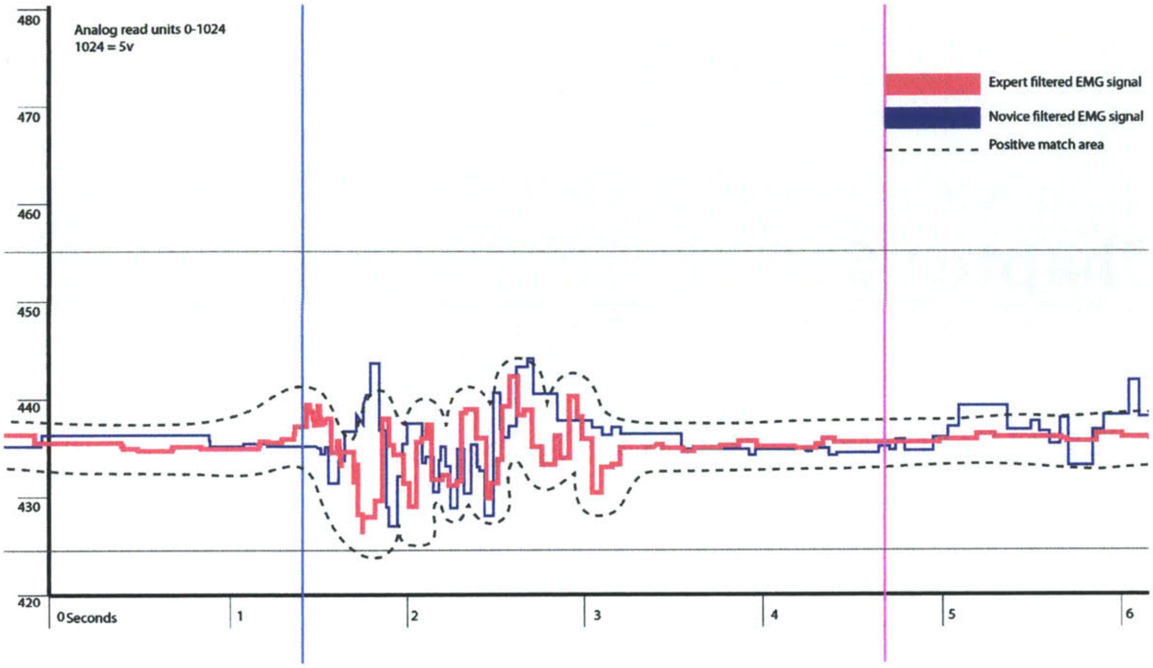


Figure 5-1: Overlay of master's EMG data and student's EMG data showing positive match boundaries.

user when the angle of the arm differed from that of the control data, in that the LED changed from a full strip of green light to a small single red light. Just a slight adjustment of the elbow or shoulder immediately corrected the posture of the participant and the red lights changed to green. This clear change from negative feedback to positive allowed the user to immediately understand that they were moving in a way that did not match the master craftsman's data. Figure 5-2 shows a comparison of the participant's 'incorrect' movement on the left to the 'correct' movement on the right.

In addition to monitoring the participants of the preliminary tests, a questionnaire was distributed to those who took part in the final experiments with the pottery wheel, which can be found in its entirety in Appendix B. The questionnaire consisted of simple inquiries such as 'Was the visual display helpful in understanding how to better perform the task' and 'Would you feel comfortable solely relying on the visual display (without an instructor present)?' The answers to this questionnaire will provide the feedback I need to further develop the sleeve in a way that makes it

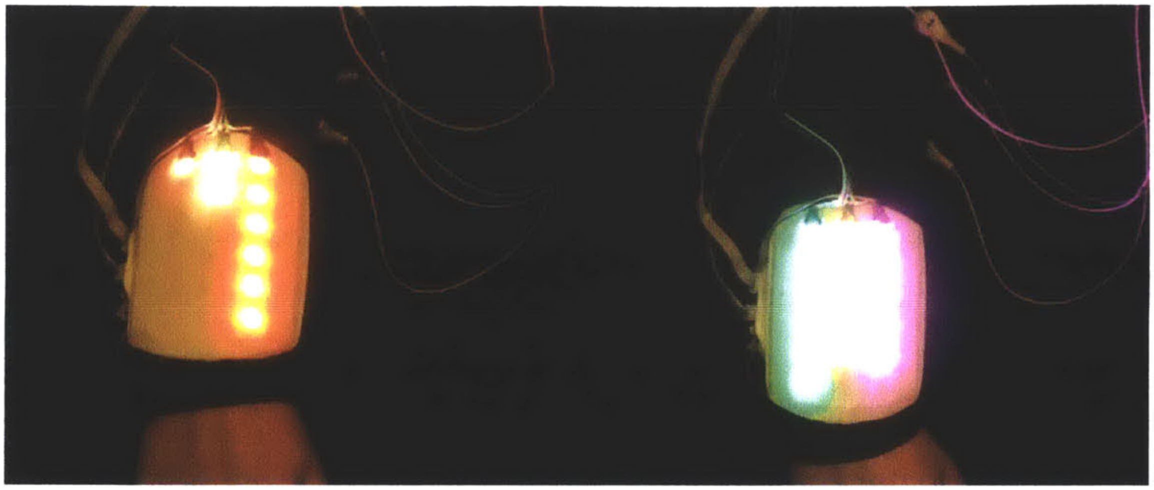


Figure 5-2: Comparison of negative feedback to positive feedback through the LED display.

more user friendly and adaptable to fields of study other than ceramics.

One response that I found to be useful in informing the next steps of this thesis is that the user found the LED display to be helpful only at the beginning; they felt that during the process of performing the task, the EMG data reduced in accuracy and created a more challenging learning environment. It was at this point that increasing the thresholds of the system produced a more positive result and therefore a more positive response from the user.

The users felt that the device did not cause any discomfort while performing the task, but one user suggested that the visual feedback could be better understood if it were projected onto a surface in front of the user. Particularly in the field of ceramics, the hand and forearm are moved into various positions, sometimes making it a challenge to properly read the LED display; if the feedback were an optional projection, the question of appropriate arm positions would be eliminated. None of the users felt that the current visual display provides the user with enough information to remove the instructor completely from the learning environment. Further advancements to the sensory data collection could provide more specific feedback regarding direction of movement, which the users stated they would then feel more comfortable learning without an instructor present in the classic sense of the word.

5.2 Next Steps

The set up of a control data group would be the next step I take in authenticating the claims made in this thesis. This control group would consist of 3 master craftsmen, each performing a task 20 times. The mean of each set of data then becomes the information to which the student's data is compared to. A minimum of 20 students would be asked to perform the same task, half with the aid of the visual display and half without. I would then be able to determine if the visual display had an impact on the learning process through the evaluation of the data from the students who utilized the display as compared to those who did not.

During the final experiments with the pottery wheel, it was clear that the visual feedback provided important information to the user regarding the initial techniques one must learn in order to move forward in the study of ceramics. Figure 5-3 shows two students attempting to center their clay, the student on the right utilized the wearable device while the student on the left did not. Although it is not clear in the photographs, it was clear during the experiment that the student without the wearable device found it much more challenging to center the clay.

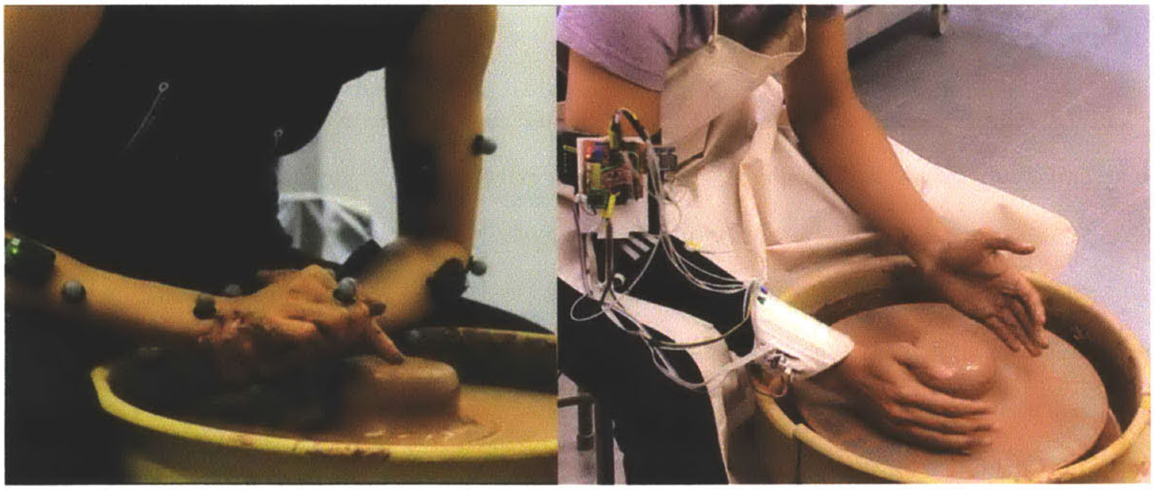


Figure 5-3: Centered clay of the students.

Through the recording of both the master craftsman and apprentice's movements using motion tracking sensors in the experiments performed thus far, it has become clear that motion tracking video in conjunction with EMG feedback give an extremely accurate digital representation of the craft. The digital simulation and EMG readings allow one to understand the movements made by the participant without needing to watch the action as it is performed. This data could be used for a variety of purposes including projected models to create a three-dimensional learning environment, or simply creating an accurate archive of movements made by masters of a particular craft. Digital recordings of both motion tracking and EMG nature would allow one to teach from a remote location, be it in another city or another continent.

Of course, with the cost of creating a controlled environment and setting up all the necessary motion-tracking equipment, this form of recording one's data is not the most cost effective solution. When budget is a concern, I propose the use of the wearable sleeve with EMG band and visual display. The device will provide similar feedback when performing a task, but is not nearly as involved to prepare. The user would not need to own or prepare any sort of motion tracking sensors and cameras, thus forming a dependency on the visual feedback of the LED display.

Chapter 6

Conclusion

In contrast to a visuo-centered worldview, the traditional arts and crafts are largely tactile-centered. It is possible that we could benefit by augmenting the way in which we interact in the environment. This could be done by utilizing smart tools or smart devices, which some might argue takes away from the point of these arts. It is a valid argument, however I believe it might open up possibilities for a different group of people that enjoy technology and believe that technology goes hand in hand with the arts. Based on the aforementioned proposed case studies, I propose that tactile skills can be taught to another person by augmented communication, which is similar to tactile communication, rather than through verbal and visual communication only. Art, craft and design ventures are creative in nature; they require the implementation of conceptual ideas in the design of materially embodied artifacts [6]. While design and craft processes are usually considered to represent a high level of cognitive and motor skill control, there is little research that reveals the neurological basis of these skills [8]. In conclusion, over the past 10 years, tremendous progress has been made in our understanding of the computational aspects of motor skill learning. The exciting challenges ahead are to understand the learning of real-world tasks and the neural implementation of the underlying processes. The success of this research field will be measured by whether the theories can inform behavior models from master craftsmen in the arts or inspire new way of interacting with materials.

6.1 Contribution

In this thesis I have attempted to illustrate opportunities in the area of hand making by augmenting the way in which we currently perform hand made crafts or fabrication. I argued that if we want to preserve crafts and all the rich knowledge that comes with making things with our hands, we need to acknowledge the way technology is moving forward and bring it to today's making processes.

I outlined a context of work, the demands of today's complex physical tasks and tomorrows desired artifacts, necessitating infused digital information within learning processes. I then introduced the foundation of this thesis, a system that uses principles of sensory motors that offer possibilities to augment our learning process by providing feedback where it's needed by introducing mechanisms to systematically improve performance further. I described the design of a wearable device and demonstrated its functionality and programmability. Useful applications were outlined by showing the experiments and feedback provided by the subjects that took part in the experiment. Finally, I showed a working prototype that embodied the hardware and system descriptions while testing the embodied signals in a physical implementation of a new way of thinking.

6.2 Future Work

I foresee the use of the device discussed in this thesis not only in the field of the arts, but also as a tool to help one redevelop a skill they may have lost due to a stroke or disability. A trainer or doctor could record data as it pertains to rehabilitation of a particular muscle, which the patient could then take home and practice their movement until it matches what was prescribed to them. The doctor would have the ability to monitor the data produced by the device worn by the patient, and adjust the code accordingly to increase or decrease the difficulty of the motor skills at hand. Physical therapy and occupational therapy practice could be heavily impacted by such a device as the length of time it takes for a patient to regain a skill could be drastically reduced.

Self-teaching is another area of discipline that could be heavily impacted by such a device. If someone were to desire a new skill, they could research the techniques involved with such a skill and download the master craftsman's EMG data on the spot in order to upload to their personal device. This data would be used to shape the learning environment in which the user acquires the skill at hand through the activation of the haptic senses. No longer would one need to attend a class, seminar, or conference; open source learning could be made available to anyone with the desire to learn. For example, a dance student in New York City could wear a body suit equipped with electrodes to record EMG data, which is then getting compared to the EMG data of a professional dancer in London. The visual display would allow the student in New York to understand how their technique compares to the professional abroad, thus improving their learning experience better than if audio/visual information was the only form of communication.

It is my goal to continue refining the code that allows the device to be utilized in a meaningful way. Through the experiments, I found that the only way to produce a positive result was to increase the thresholds in which the data was considered a match to the master craftsman. This result leads me to believe that further refinement of the components and the code will allow the user to learn a skill with a high degree of efficiency through lower threshold levels, producing a motor skill that closely resembles that of the master.

Appendix A

Code

```
...

#include <Adafruit_NeoPixel.h>
#include <SPI.h> // Included for SFE_LSM9DS0 library
#include <Wire.h>
#include <SFE_LSM9DS0.h>
#include <SdFat.h>
#include <SdFatUtil.h>
#include <MovingAvarageFilter.h>
MovingAvarageFilter movingAvarageFilter(20);
// define FreeRam()
// store error strings in flash to save RAM
#define EMG_PIN1   A0  // Microphone is attached to this analog pin
#define EMG_PIN2   A1  // Microphone is attached to this analog pin
#define EMG_PIN3  A2  // Microphone is attached to this analog pin
#define PIN1 7
#define PIN2 6
#define PIN3 5
#define error(s) sd.errorHalt_P(PSTR(s))
#define LSM9DS0_XM  0x1D // Would be 0x1E if SDO_XM is LOW
#define LSM9DS0_G   0x6B // Would be 0x6A if SDO_G is LOW
#define ledPin  13
// LED connected to digital pin 13
#define buttonPin 9
```

```
// button on pin 4
#define PRINT_SPEED 20
// 500 ms between prints
LSM9DS0 dof(MODE_I2C, LSM9DS0_G, LSM9DS0_XM);
#define PRINT_CALCULATED
SdFat sd;
SdFile myFile;

ArduinoOutStream cout(Serial);
int value = LOW;
// previous value of the LED
int buttonState;
// variable to store button state
int lastButtonState;
 // variable to store last button state
int blinking;
// condition for blinking - timer is timing
int fractional;
// variable used to store fractional part of time
int counter = 0 ;
int counterR; // counter for Array
int OveConter;
int indexR = 0;
int BLINK = 0;
int BLINKemg = 0;
int BLINKOLD =0;
int BLINKOLDemg =0;
int lengthRead = 0;
int PIXEL;
int PIXELemg;
int arrBlock =0;
int EMGarrBlock = 0;
int percent;
int pos = 0;
int brightness = 0;    // how bright the LED is
int fadeAmount = 5;    // how many points to fade the LED by
```

```
int c;
int s;
int accumProgress;
int counter1;
int initialRead = 0;
int lowerLimit = 0;
int EMGlowerLimit = 0;
int pxlOn ;
const int numReadings = 10;
int readings0[numReadings];      // the readings from the analog input
int readings1[numReadings];      // the readings from the analog input
int readings2[numReadings];      // the readings from the analog input
int startPx =0;
int myIndex = 0;                  // the index of the current reading
int total1 = 0;                  // the running total
int total2 = 0;                  // the running total
int total3 = 0;                  // the running total
int average1 = 0;                // the average
int average2 = 0;                // the average
int average3 = 0;                // the average
int readS = 0;                 // the average
int upperLimit ;
int EMGupperLimit =0;
float  roundGrader ;
float roundGraderT =0;
float EMGroundGrader;
int overallProgCounter;
int EMGoverallProgCounter;
int EMGoverallProgress;
long lng = 100;
long nlng = 100;
long interval = 100;
// blink interval - change to suit
unsigned long previousMillis = 0;
 // variable to store last time LED was updated
unsigned long newMillis = 0;
```

```
// variable to store last time LED was updated
unsigned long startTime ;
 // start time for stop watch
unsigned long elapsedTime ;// elapsed time for stop watch
long  lg ,lg2 ,lg3 ,lg4 ;
unsigned long time;
int Pxlevel = 0;
int level = 0;
int counterCagri=0;
int counterEMG =0;
const int chipSelect = 10;
char fileName[] = "JAYCENT3.CSV";
char c1 ,c2 ,c3 ,c4 ,c5 ,c6 ;

boolean iterateSwitch = false;
boolean writeWhileCheck = false;
boolean readSwitch = false;
boolean iscalibrated = false;
boolean isCalibrating = false;
boolean mainArr = false;
boolean EMGmainArr = false;
float hInCal = 0;
float pInCal = 0;
float rInCal = 0;
float pitch, yaw, roll, heading;
float hRaw,rRaw,pRaw;
float f2 ,f3 ,f4 ;
float dataInArray[2000];
int EMG1[2000];
int EMG2[2000];
int EMG3[2000];
float lgtCounter = 0.00;
float lgtCounter2 = 0.00;
int stripCounter;
int stripCounter2;
int stripCounterEMG;
```

```
  float outputEMG1 = 0;
  float outputEMG2 = 0;
  float outputEMG3 = 0;

Adafruit_NeoPixel strip1 = Adafruit_NeoPixel(7, PIN1, NEO_GRB + NEO_KHZ800);
Adafruit_NeoPixel strip2 = Adafruit_NeoPixel(7, PIN2, NEO_GRB + NEO_KHZ800);
Adafruit_NeoPixel strip3 = Adafruit_NeoPixel(7, PIN3, NEO_GRB + NEO_KHZ800);
uint32_t magenta = strip2.Color(255, 0, 255);
uint32_t Yellow = strip2.Color(255, 218, 3);
uint32_t coolBlue = strip2.Color(3, 255, 240);
uint32_t coolGreen = strip2.Color(161, 255, 3);

uint32_t off = strip2.Color(0, 0, 0);
void setup()
{
  Serial.begin(115200);
  while (!Serial) {} // wait for Leonardo
  cout << pstr(”Type␣any␣character␣to␣start\n”);
  while (Serial.read() <= 0) {}
 delay(400); // catch Due reset problem
  strip1.begin();
  strip2.begin();
  strip3.begin();
  strip1.setBrightness(100);
  strip2.setBrightness(100);
  strip3.setBrightness(100);
  //Set for LED brightness.  0 (off) to 255 (max brightness)
  strip1.show();
  strip2.show();
 strip3.show(); // Initialize all pixels to 'off'
   pinMode(ledPin, OUTPUT);
   // sets the digital pin as output

   pinMode(buttonPin, INPUT);
   // not really necessary, pins default to INPUT anyway
   digitalWrite(buttonPin, HIGH);
```

```
    // turn on pullup resistors. Wire button so that press shorts pin to ground.
    Serial.print("Initializing␣SD␣card...");
    if (!sd.begin(chipSelect, SPI_FULL_SPEED)) sd.initErrorHalt();

    pinMode(SS, OUTPUT);
   // open the file for write at end like the Native SD library

   uint32_t status = dof.begin();

   Serial.print("LSM9DS0␣WHO_AM_I's␣returned:␣0x");
   Serial.println(status, HEX);
   Serial.println("Should␣be␣0x49D4");
   Serial.println();
   // read and print test
   // initialize all the readings to 0:
   for (int thisReading1 = 0; thisReading1 < numReadings; thisReading1++)
         readings0[thisReading1] = 0;

   for (int thisReading2 = 0; thisReading2 < numReadings; thisReading2++)
         readings1[thisReading2] = 0;

  for (int thisReading3 = 0; thisReading3 < numReadings; thisReading3++)
         readings2[thisReading3] = 0;

}

void loop()
{
     // check for button press
   buttonState = digitalRead(buttonPin);
   // read the button state and store
   printGyro();  // Print "G: gx, gy, gz"
   printAccel(); // Print "A: ax, ay, az"
   printMag();   // Print "M: mx, my, mz"
// Print the heading and orientation for fun!
   printHeading((float) dof.mx, (float) dof.my);
```

```
  printOrientation(dof.calcAccel(dof.ax), dof.calcAccel(dof.ay), dof.calcAccel(dof.az
  hRaw = heading;
  smoothing();
  runtimer();
//  Serial.println("Welcome to the main loop, please come again");
  delay(PRINT_SPEED);
}

void EMGpixelOn(int grade2){

stripCounterEMG = stripCounterEMG+grade2;
if(stripCounterEMG<0)
stripCounterEMG=0;
BLINKemg = stripCounterEMG;

   for(int i=0;i<7;i++){
     strip2.setPixelColor(i,0,0,0);


   }

  if (BLINKemg<strip2.numPixels()) {
      strip2.setPixelColor(BLINKemg-1, Yellow);
       delay(10);
       for (int i=0;i<BLINKemg-1;i++)
  {
        strip2.setPixelColor(i,Yellow);
        delay(10);
  }
      strip2.show();
      delay(10);
  }
  else if (stripCounterEMG > 6){
    stripCounterEMG =0;
          strip2.show();
          colorWipe(strip2.Color(0,0 , 0), 50); // Green
 }
```

```
}
void colorWipe(uint32_t c, uint8_t wait) {
  for(uint16_t i=0; i<strip2.numPixels(); i++) {
      strip2.setPixelColor(i, c);
      strip2.show();
      delay(wait);
  }
}
void smoothing(){

// subtract the last reading:
  total1= total1 - readings0[myIndex];
  total2= total2 - readings1[myIndex];
  total3= total3 - readings2[myIndex];

  readings0[myIndex] = analogRead(EMG_PIN1);
  readings1[myIndex] = analogRead(EMG_PIN2);
  readings2[myIndex] = analogRead(EMG_PIN3);

  total1= total1 + readings0[myIndex];
  total2= total2 + readings1[myIndex];
  total3= total3 + readings2[myIndex];
  // advance to the next position in the array:
  myIndex = myIndex + 1;

  // if we're at the end of the array...
  if (myIndex >= numReadings)
    // ...wrap around to the beginning: S
    myIndex = 0;
// calculate the average:
  average1 = total1 / numReadings;
  average2 = total2/ numReadings;
  average3 = total3 / numReadings;

  outputEMG1 = round (movingAvarageFilter.process(average1));
  // here we call the fir routine with the input. The value 'fir' spits out is stored
```

```
  outputEMG2 = round (movingAvarageFilter.process(average2));
  // here we call the fir routine with the input. The value 'fir' spits out is stored
  outputEMG3 = round (movingAvarageFilter.process(average3));
  // here we call the fir routine with the input. The value 'fir' spits out is stored

  delay(5);          // delay in between reads for stability
}

void beginingLigh(){

  for (int i=0; i <= 255; i++){
    for (int j= 5 ; j >= 0; j--){
      delay(2);

strip1.setBrightness(i);
strip2.setBrightness(i);
strip3.setBrightness(i);

//uint32_t red = strip.Color(255, 0, 255);
//uint32_t magenta = strip.Color(255, 0, 255);
strip1.setPixelColor(i/50, i, i,0);
strip2.setPixelColor(i/50, i, i,0);
strip3.setPixelColor(i/50, i, i,0);



strip1.show(); // Initialize all pixels to 'off'
strip2.show(); // Initialize all pixels to 'off'
 strip3.show(); // Initialize all pixels to 'off'
 startPx++;
   }
  }

}
void colorWipe3(uint32_t c, uint8_t wait) {
  for(uint16_t i=0; i<strip2.numPixels(); i++) {
      strip1.setPixelColor(i, c);
```

```
      strip2.setPixelColor(i, c);
      strip3.setPixelColor(i, c);
      strip1.show();
      strip2.show();
      strip3.show();
      delay(wait);
  }
}
int accTreshole = 10;
void itterate(){

     if (fabs(dataInArray[counterCagri]-pRaw)<accTreshole){
         roundGrader++;
     }

    if (counterCagri==lengthRead){
              counterCagri=0;
            }

    else{
         float temp = ((float)lengthRead) / 36 ;
         arrBlock = (int)temp;
         if (mainArr == false){
             upperLimit = arrBlock;
             mainArr = true;
         }
                if( counterCagri == upperLimit){
                    if(roundGrader>=((float)arrBlock)/2){
                         lowerLimit+=arrBlock;
                         upperLimit+=arrBlock;
                         overallProgCounter++;
                         pixelOn(1);
                         roundGrader=0;
                    }

                 else {
```

```
                 counterCagri = 0;
                 roundGrader=0;
                 lowerLimit=0;
                 upperLimit=arrBlock;
                 overallProgCounter=0;
                 overallProgress(0);
                 pixelOn(0);
                 }

                 if(overallProgCounter==6){
                  overallProgress(1);


                 }
               }


              }
                counterCagri++;
    }

    int emgTreshold = 10;
void itterate2(){
            Serial.print(”counterEMG␣:”);
            Serial.println(counterEMG);
             Serial.print(”EMG1[counterEMG]”);
            Serial.println(EMG1[counterEMG]);

     if (fabs(EMG1[counterEMG]-outputEMG1)< emgTreshold ){
         EMGroundGrader++;
     }
     else{
     }

   if (counterEMG==lengthRead){
          counterEMG=0;
         }
```

```
else{
    float temp = lengthRead / 36 ;
    EMGarrBlock = (int)temp;
    if (EMGmainArr == false){
      EMGupperLimit = EMGarrBlock;
      EMGmainArr = true;
    }

                       if( counterEMG == EMGupperLimit){

                         if(EMGroundGrader>=((float)EMGarrBlock)/2){
                                EMGlowerLimit+=EMGarrBlock;
                                EMGupperLimit+=EMGarrBlock;
                                EMGoverallProgCounter++;
                                EMGpixelOn(1);
                                EMGroundGrader=0;
                         }

                     else {
                     counterEMG = 0;
                     EMGroundGrader=0;
                     EMGlowerLimit=0;
                     EMGupperLimit=arrBlock;
                     EMGoverallProgCounter=0;
                     EMGoverallProgress= 0;
                     EMGpixelOn(0);
                     }

                     if(EMGoverallProgCounter==6){
                       overallProgress(1);

                     }
                 }

            }
              counterEMG++;
```

```
    }

    void printGyro()
{
  // To read from the gyroscope, you must first call the
  // readGyro() function. When this exits, it'll update the
  // gx, gy, and gz variables with the most current data.
  dof.readGyro();
}

void printAccel()
{
  // To read from the accelerometer, you must first call the
  // readAccel() function. When this exits, it'll update the
  // ax, ay, and az variables with the most current data.
  dof.readAccel();

}

void printMag()
{
  // To read from the magnetometer, you must first call the
  // readMag() function. When this exits, it'll update the
  // mx, my, and mz variables with the most current data.
  dof.readMag();
}

void printHeading(float hx, float hy)
{

  if (hy > 0)
  {
    heading = 90 - (atan(hx / hy) * (180 / PI));
  }
  else if (hy < 0)
  {
```

```
    heading = - (atan(hx / hy) * (180 / PI));
  }
  else // hy = 0
  {
    if (hx < 0) heading = 180;
    else heading = 0;
  }
}
void printOrientation(float x, float y, float z)
{

  pitch = atan2(x, sqrt(y * y) + (z * z));
  roll = atan2(y, sqrt(x * x) + (z * z));
  pitch *= 180.0 / PI;
  roll *= 180.0 / PI;
  pRaw=pitch;
  rRaw=roll;
}

 float  RpitchMapped = 0 ;
 float  SpitchMapped = 0 ;
 float  REMGmapped = 0 ;
 float  SEMGmapped = 0 ;
 float dist;
 int realP ;

 int ro=0;int go=0;int bo=0;
void overallProgress(int OVERALLgrade){

  RpitchMapped =  map (dataInArray[counterCagri],-30,70,0,100);
  SpitchMapped =  map (pRaw,-30,70,0,100);

  REMGmapped = map (EMG1[counterEMG],250,750,0,100);
  SEMGmapped = map (outputEMG1,250,750,0,100);

  dist =  (RpitchMapped-SpitchMapped);
```

```
  if(dist>-6 && dist<=0){
      ro=(255/6)*-dist;
      go=255-(255/6)*-dist;
      realP=-dist;

  }

  else{
    ro=255;
    go=0;
    realP=6;

  }

  solid1(255,0,0);
  //strip3.show();

}
void solid1(uint16_t r, uint16_t g, uint16_t b)
{

  for(int i=0;i<7;i++){
    strip3.setPixelColor(i,0,0,0);
        strip1.show();

  }

  for (int i=0;i<6-realP;i++)
  {

    strip3.setPixelColor(i,ro,go,bo);
    strip3.show();
    delay(10);
  }
}
```

```
 int r1 = 0;
  int g1 = 0 ;
  int b1= 0;
void pixelOn(int grade){

if(grade==0){
    BLINK=0;
    Pxlevel = 0;
}
else{
    BLINK +=grade;
    if(BLINK<0){
    BLINK=0;
    }
    BLINK = BLINK;
    if (BLINK>=7){
    Pxlevel++;
    BLINK = 0;
 }
    nextPixel();
    solid(255,0,0);
  }
   if (Pxlevel > 6){
 Pxlevel= 0;
 }


}
void nextPixel(){
  if (Pxlevel == 0){
    r1 = 255;
    g1 = 0 ;
    b1= 0;


  }
  if (Pxlevel ==1 ){
```

```
    r1 = 255;
    g1 = 0 ;
    b1= 255;

  }
  if (Pxlevel == 2){
    r1 = 0;
    g1 = 0 ;
    b1= 255;
  }
  if (Pxlevel == 3){
    r1 = 3;
    g1 = 255 ;
    b1= 240;
  }if (Pxlevel == 4){
    r1 = 255;
    g1 = 218 ;
    b1= 3;
  }
  if (Pxlevel == 5){
    r1 = 161;
    g1 = 255 ;
    b1= 3;
  }
  if (BLINK > 7){
    BLINK =0;

 }

}

void solid(uint16_t r, uint16_t g, uint16_t b)
{

  for(int i=0;i<7;i++){
    strip1.setPixelColor(i,0,0,0);
```

```
        strip1.show();

  }

  for (int i=0;i<BLINK;i++)
  {

    strip1.setPixelColor(i,r1,g1,b1);
    strip1.show();
    delay(10);
  }
}
 void runtimer(){
/
     if (buttonState == LOW && lastButtonState == HIGH  && !iscalibrated && blinking =
// check for a high to low transition
      // if true then found a new button
      //press while clock is not running - start the clock
      isCalibrating=true;
      Serial.println(”PRESSED”);
      iscalibrated= true;
      startTime = millis(); // store the start time
      blinking = true; // turn on blinking while timing
      lastButtonState = buttonState;
      // store buttonState in lastButtonState, to compare next time
//      Serial.print(”time lapsed:”);         // add one zero
//      Serial.println(startTime);  // print fractional part of time
 }
      if(isCalibrating){
            hInCal += hRaw;
            pInCal += pRaw;
            rInCal += rRaw;

            if (counter == 5){
              while (startPx < strip1.numPixels()){
                  beginingLigh();
```

```
                }
              colorWipe3(strip1.Color(0,0 , 0), 50); // Green
              colorWipe3(strip2.Color(0,0 , 0), 50); // Green
              colorWipe3(strip3.Color(0,0 , 0), 50); // Green
               Serial.println("COUNTER_DONE");
               isCalibrating = false;

               hInCal = hInCal/6;
               pInCal = pInCal/6;
               rInCal = rInCal/6;
             }

     counter++;

      }
    delay(30);  // short delay to debounce switch

if(iscalibrated)
  {
   hRaw = hRaw-hInCal;
   pRaw = pRaw-pInCal;
   rRaw = rRaw-rInCal;
   iterateSwitch = true;
   writeWhileCheck = true;
  }

  else if (buttonState == LOW && lastButtonState == HIGH
      && blinking == true && iscalibrated){     // check for a high to low transiti
     // if true then found a new button press
     // while clock is running - stop the clock and report

      elapsedTime =   millis() - startTime;// store elapsed time
      blinking = false;// turn off blinking, all done timing
      lastButtonState = buttonState;
     // store buttonState in lastButtonState, to compare next time
     // routine to report elapsed time
```

```
      Serial.print( (int)(elapsedTime / 1000L));
       // divide by 1000 to convert to seconds - then cast to an int to print
      Serial.print(”.”);  / print decimal point
      // use modulo operator to get fractional part of time
     fractional = (int)(elapsedTime % 1000L);
     // pad in leading zeros - wouldn't it be nice if
     // Arduino language had a flag for this? :)
     if (fractional == 0)
        Serial.print(”000”);        // add three zero's
     else if (fractional < 10)    // if fractional < 10 the 0 is ignored giving a w
        Serial.print(”00”);         // add two zeros
     else if (fractional < 100)

 }

 else{
    lastButtonState = buttonState;
     // store buttonState in lastButtonState, to compare next time
 }

 // blink routine - blink the LED while timing
 // check to see if it's time to blink the LED; that is, the difference
 // between the current time and last time we blinked the LED is larger than
 // the interval at which we want to blink the LED.

 if ( (millis() - previousMillis > interval) ) {
    if (blinking == true){
       newMillis = millis()-startTime;
 //if the LED is off turn it on and vice-versa.
       digitalWrite(ledPin, value);

  if (!myFile.open(”Noel7.CSV”, O_RDWR | O_CREAT | O_AT_END)) {
  sd.errorHalt(”opening␣pullCag8.CSV␣for␣write␣failed”);
}
// create test file
writeFile();
```

```
  cout << endl;

  // read and print test
  readFile();
  if (iterateSwitch){
  itterate();
  itterate2();
  overallProgress(1);
  }
cout << ”DONE_READING!”<< endl;

         if (value == LOW)
             value = HIGH;
         else
            value = LOW;
      }
      else{
         digitalWrite(ledPin, LOW); // turn off LED when not blinking
      }

   }
 }

 void readFile() {
if (readSwitch == false){
  readSwitch = true;
  // open input file
  ifstream sdin(fileName);

  // check for open error
  if (!sdin.is_open()) error(”open”);
   // if (readCounter = 0){

  // read until input fails
  while (sdin >> lg >> c1 >> f2 >> c2 >>
```

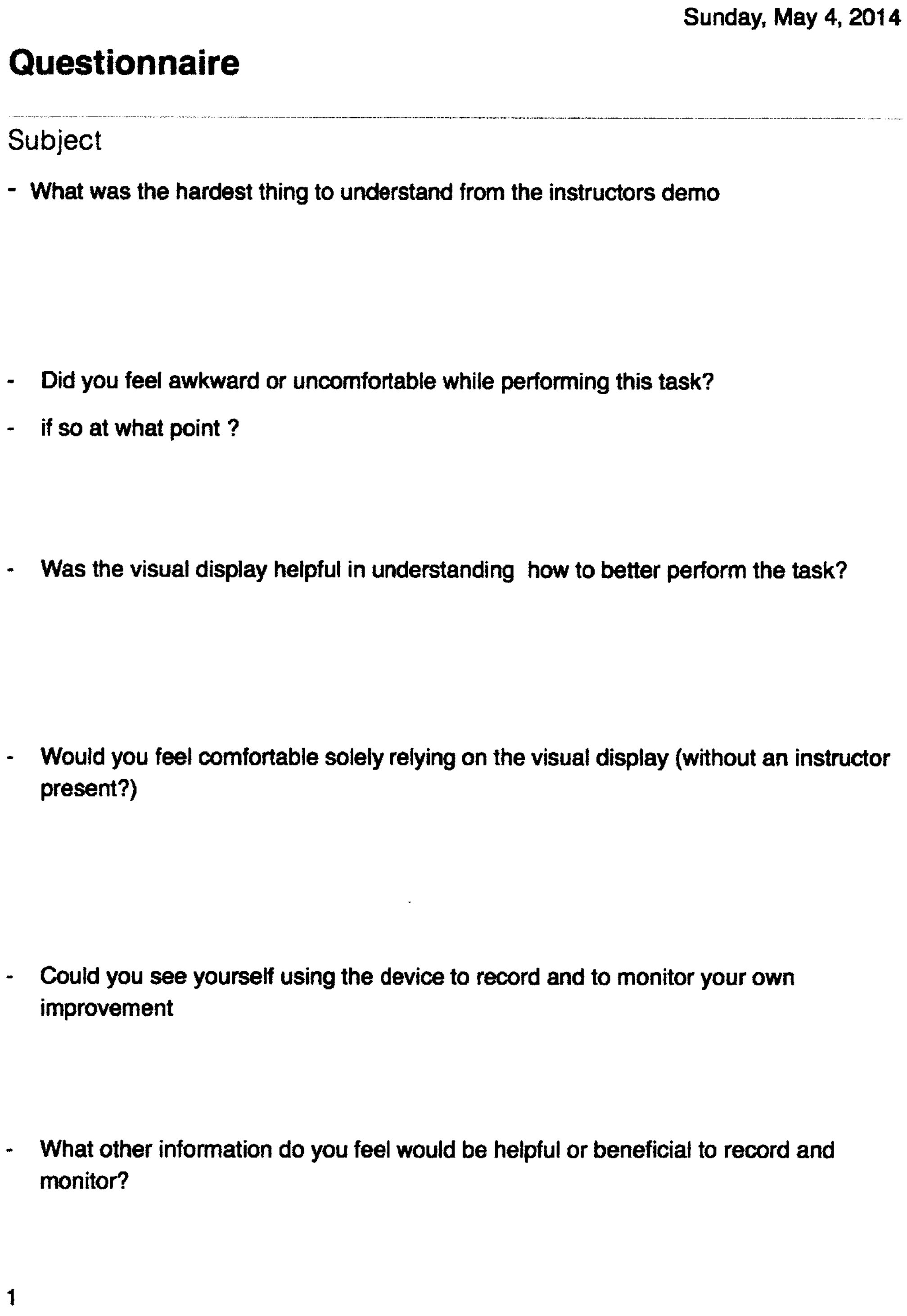
```
        f3 >> c3 >> f4 >> c4 >> lg2>> c5 >> lg3>> c6 >> lg4) {
    if (f2 != '\n'){
        dataInArray[counterR] = f3;
        EMG1[counterR] = lg2;
        EMG2[counterR] = lg3;
        EMG3[counterR] = lg4;

        counterR++;
        lengthRead = counterR;
       Serial.println (lengthRead);
       delay(50);
    }
    // error in line if not commas
    if (c1 != ',' || c2 != ',' || c3 !=
   ','|| c4 != ','|| c5 != ','|| c6 != ',') error("comma");

  }
  // Error in an input line if file is not at EOF.
  if (!sdin.eof()) error("readFile");
}
}
void writeFile() {

          myFile.print(newMillis);
          myFile.print(",");

          myFile.print(hRaw);
          myFile.print(",");

          myFile.print(pRaw);
          myFile.print(",");

          myFile.print(rRaw);
          myFile.print(",");
```

```
        myFile.print((int)outputEMG1);
        myFile.print(”,”);

        myFile.print((int)outputEMG2);
        myFile.print(”,”);
        myFile.println((int)outputEMG3);
        Serial.println(”outputEMG3”);
        myFile.close();

}
```

This code should provide enough information; if some would want to replicate the setup ...

Appendix B

Figures



Sunday, May 4, 2014

Questionnaire

Subject

- What was the hardest thing to understand from the instructors demo

- Did you feel awkward or uncomfortable while performing this task?
- if so at what point ?

- Was the visual display helpful in understanding how to better perform the task?

- Would you feel comfortable solely relying on the visual display (without an instructor present?)

- Could you see yourself using the device to record and to monitor your own improvement

- What other information do you feel would be helpful or beneficial to record and monitor?

1

Figure B-1: Questionare used with participants

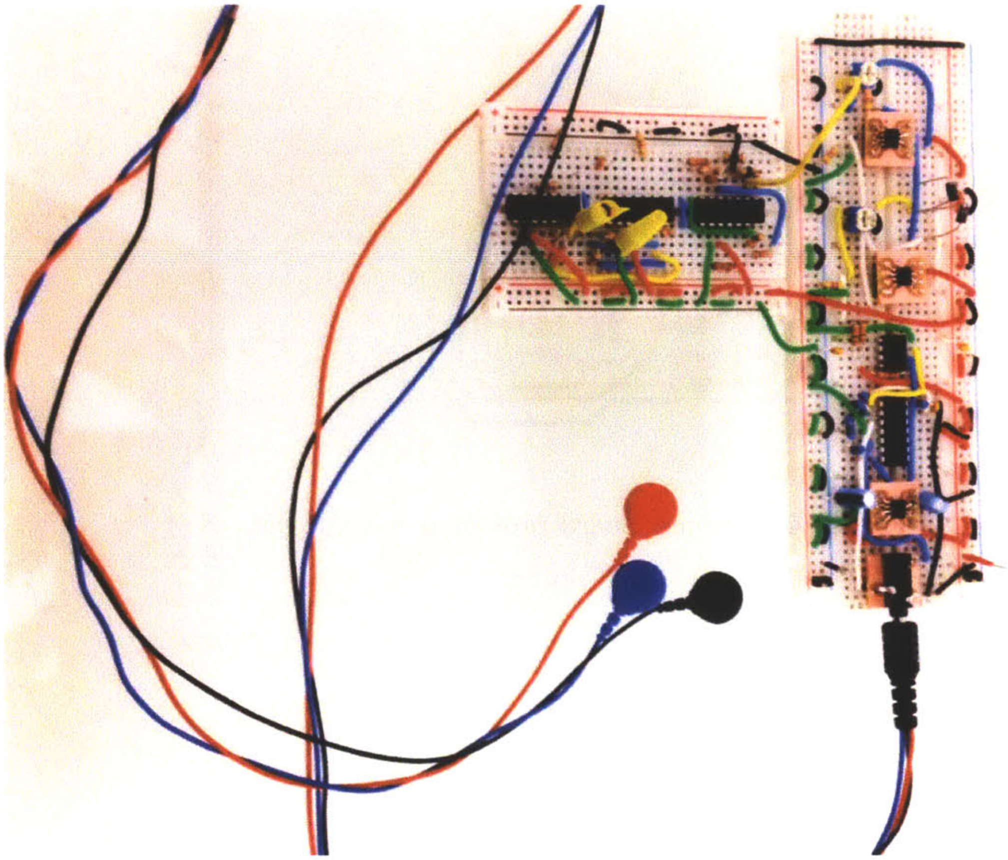


Figure B-2: Initial circuit protype

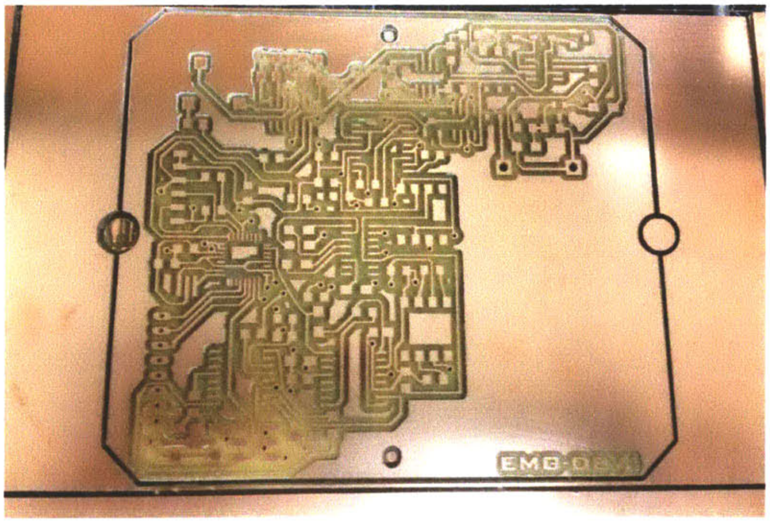


Figure B-3: Cuircuit board prototype 1, copper board milled .

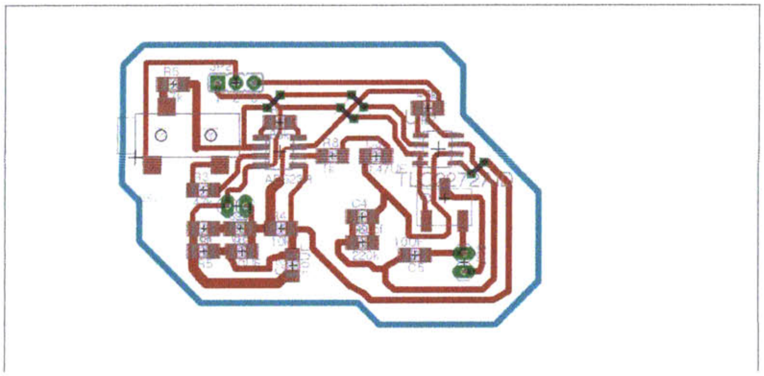


Figure B-4: Cuircuit board prototype 1, eagle file.

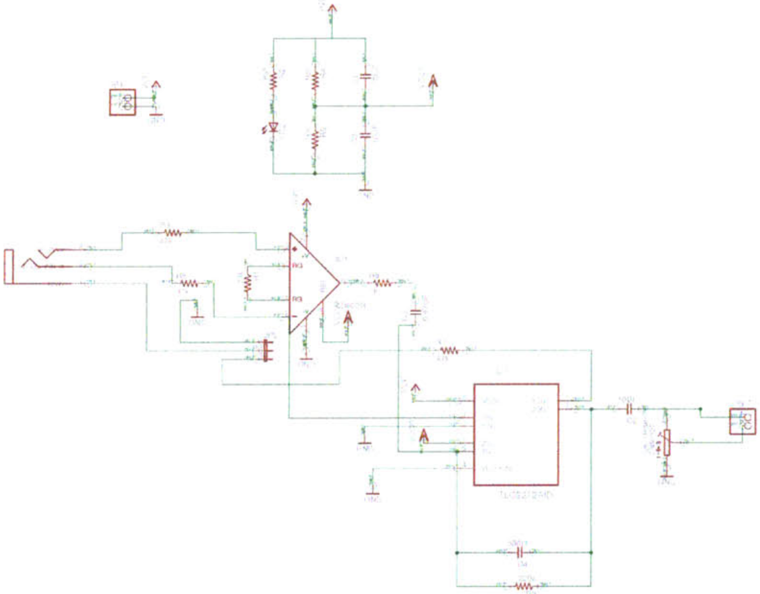


Figure B-5: Cuircuit board eagle Schematic 1, copper board milled .

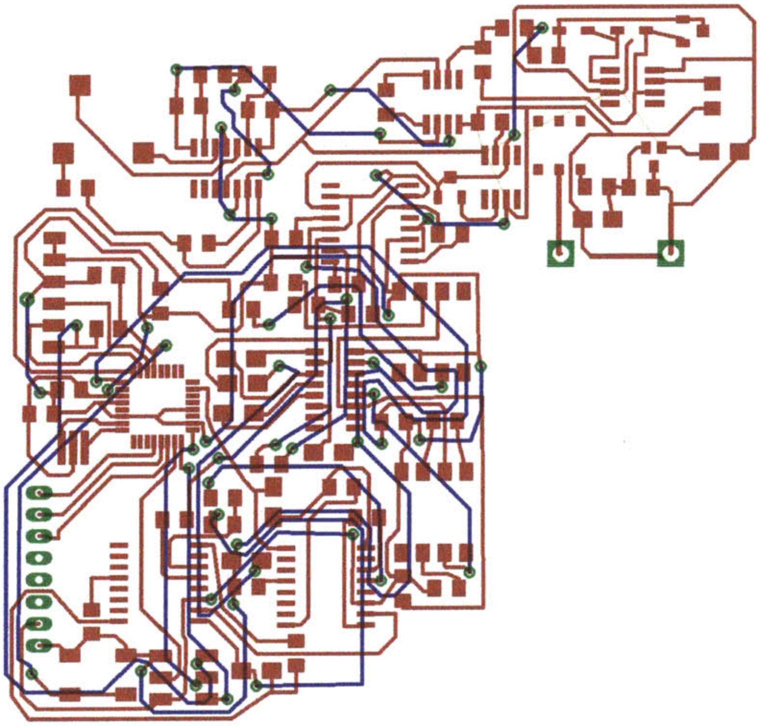


Figure B-6: Cuircuit board prototype 1, eagle file.

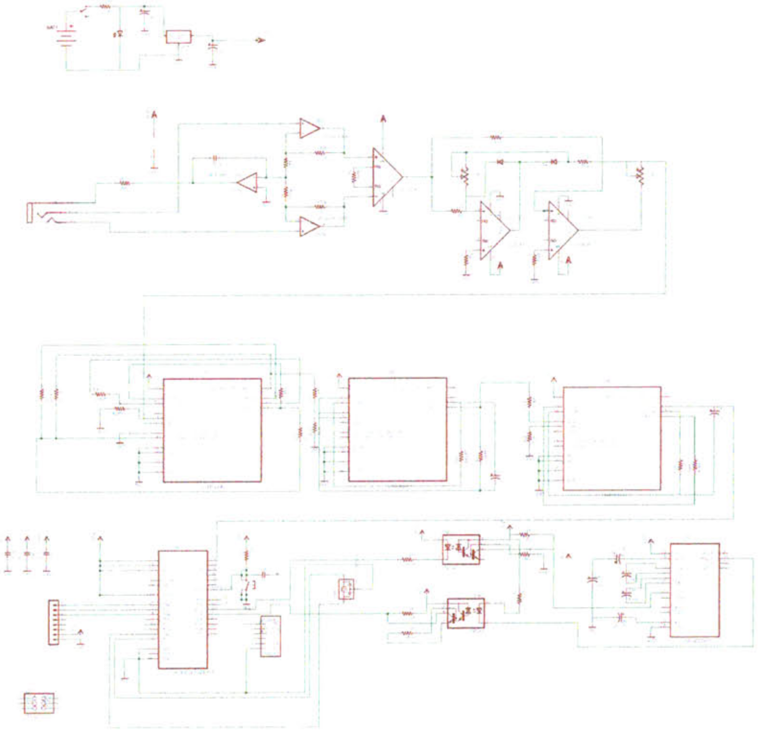


Figure B-7: Cuircuit board prototype 1, eagle schematic file.

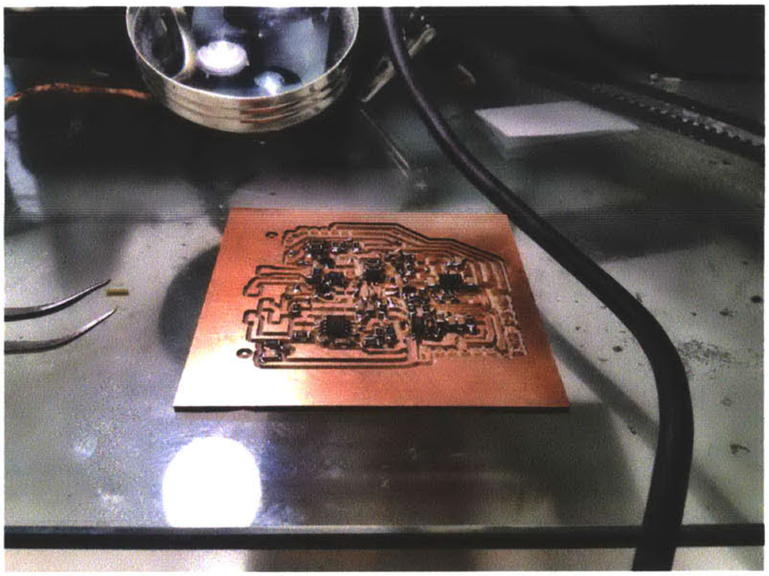


Figure B-8: uircuit board prototype 2, copper board milled , SD card reader and EMG.

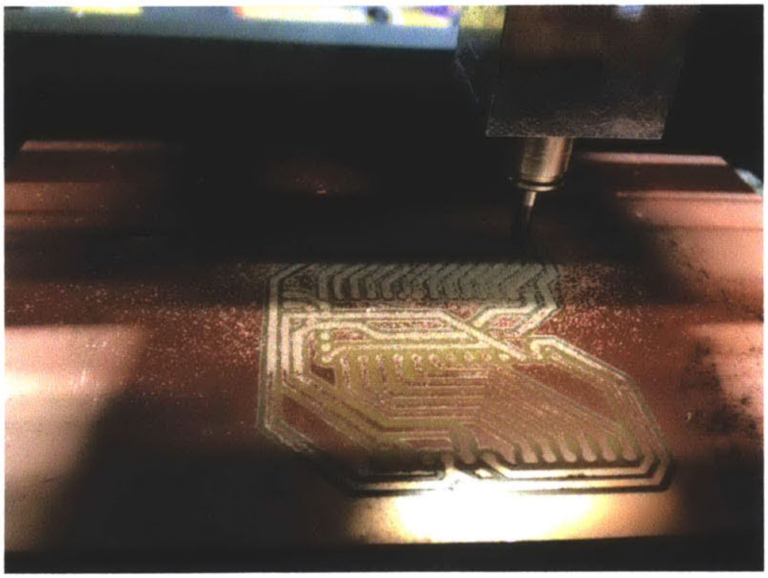


Figure B-9: Copper board milled to interface between Teensy, SD card reader and EMG.

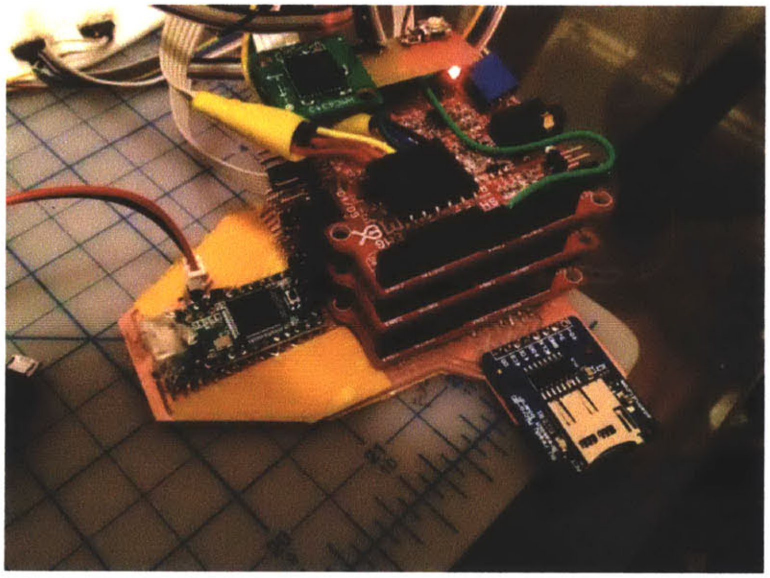


Figure B-10: Integration of all components that go in the arm band.

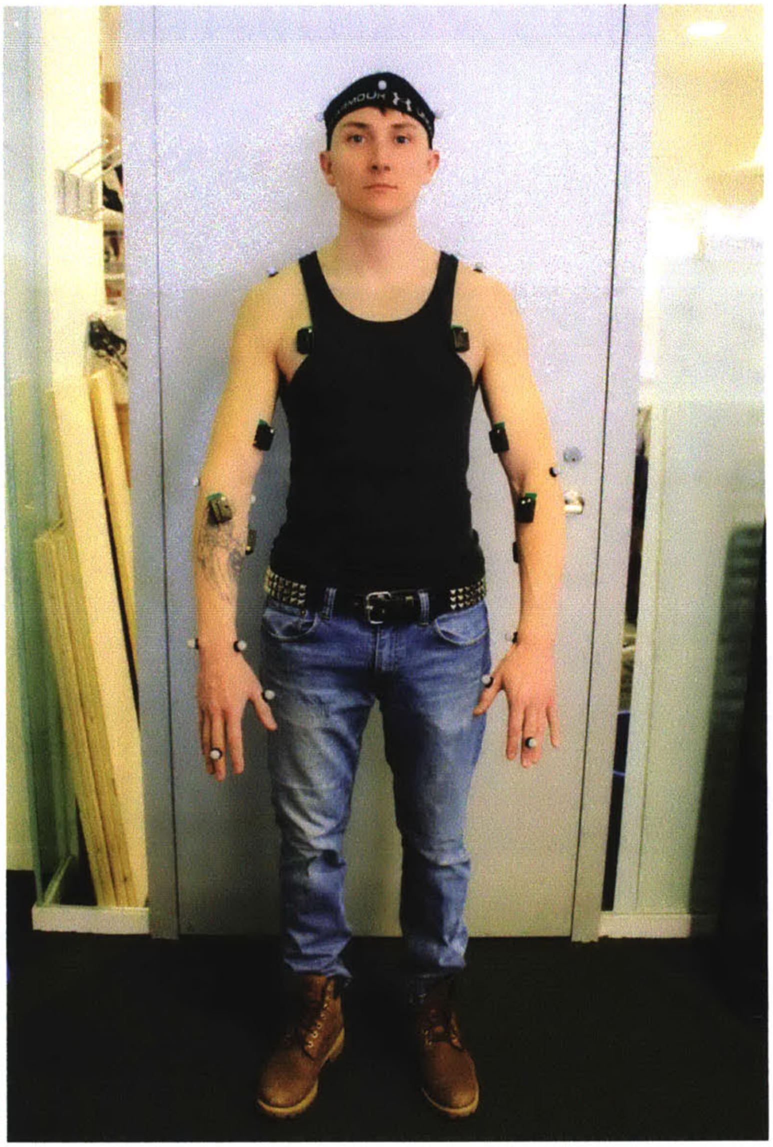


Figure B-11: Instructor wearing all components for motion tracking.

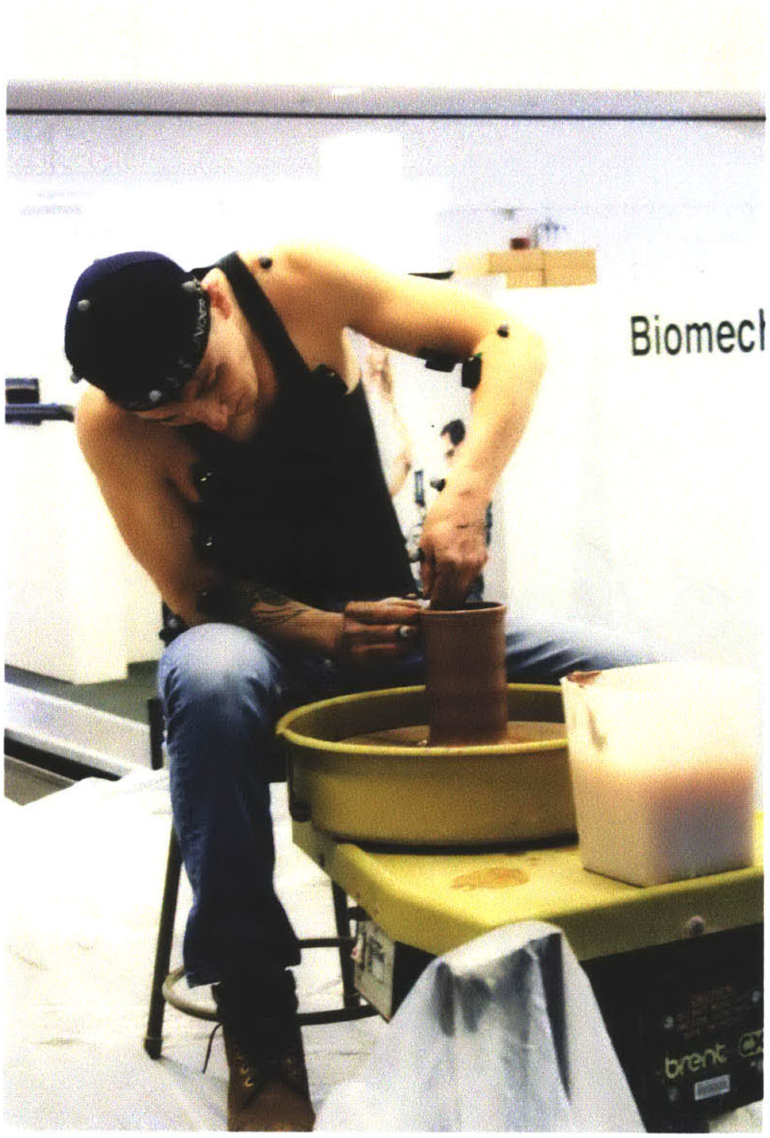


Figure B-12: Instructor working on the pottery wheel with Motion equipment on his body.

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