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The Effect of Vibrotactile Feedback on Remote Manual Task Performance

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The Effect of Vibrotactile Feedback on Remote Manual Task Performance

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
at Virginia Commonwealth University

by

Matthew Standard

Bachelor of Science
Virginia Commonwealth University, 2013

Director: Dr. Dianne T.V. Pawluk
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Virginia Commonwealth University
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Abstract

THE EFFECT OF VIBROTACTILE FEEDBACK ON REMOTE MANUAL TASK PERFORMANCE

By Matthew Standard, BS Biomedical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

Virginia Commonwealth University, 2017.

Major Director: Dr. Dianne T.V. Pawluk,
Assistant Professor, Department of Biomedical Engineering

Vibrotactile feedback offers a unique opportunity to augment or reconstruct impaired tactile sensations, whether that be in the form of enhancing prosthetics or specialized protective clothing. Important information about temperature and object slippage serve to endanger the human operator or equipment. This thesis presents three experiments which investigate amplitude modulated vibrotactile signals as a scalar dimension of roughness, the effect those signals and their locations (finger pad, forearm, bicep) have on the performance of two tasks: the sensing of temperatures simulated by vibrotactile signals and gripping an object of simulated surface texture. The results show task performance increase when the feedback and site of action are co-located for sensory tasks and decrease for manipulatory tasks.
1. Introduction

1.1 Nature of the Problem

Human operators depend on all sensory modalities to efficiently and safely complete manual tasks. The most important of the senses for ensuring efficient and safe operation is the tactile sense: individuals with impaired tactile sensing in the fingertips, even with vision, often drop or easily crush objects when manipulating them directly (Westling and Johansson, 1984; Johansson and Flanagan, 2008). In contrast, there are many instances where we perform manual tasks successfully without vision, such as in the dark or fog, including when the reaching hand occludes the object from view in most everyday tasks. In these conditions, we do not experience the same impediment as with the lack of touch.

In work environments, there are many situations in which a human operator may have a partially or completely impaired sense of touch which interferes with work or endangers the operator. Manual tasks may be inadvertently hindered by the necessity of protection from the environment by specialized gear, such as for firefighting or astronautic extravehicular activity tasks (Thompson and Benson, 2011). In these environments, protective gear may also render additional environmental sensory information useful for safety unavailable, such as with external heat and humidity for firefighters.

For upper limb amputees, the lack of tactile sensation in current prosthetics results in users requiring significant visual attentional resources for what are ordinarily simple tasks using tactile feedback, such as holding a glass of water. Two of the most desired requirements for
upper limb prostheses, as stated by users, is the addition of sensory feedback about haptic information and less use of visual attention (Cordella et al., 2016).

Currently, vibrotactile feedback is considered the best option for conveying needed tactile information: Vibrotactile, rather than electrotactile, feedback is considered more acceptable for prosthetic users (Ciancia et al., 2016). In addition, although, direct neural interfaces are under development, they have issues of stability over the implant’s lifetime (Ciancia et al., 2016).

We will consider two examples in more detail to elucidate these problems. The first example is that of astronauts performing tasks during Extravehicular Activity (EVA) in space. EVA suits have multiple layers which include a pressurized bladder to combat the vacuum of space and an outer layer to protect from micrometeoroid collisions. The necessity of the protective design limits mobility and dexterity while also removing reliable force feedback for grasping tasks. This results in the exertion of a greatly exaggerated grip force causing microfractures in the fingernail bed leading to fingernail delamination, which astronauts may already be at risk of experiencing (Opperman, et. al, 2010). Alternatively, without this over-correction, tools may slowly drift from the operator’s grip if their attention wavers. In addition, the EVA suits impede otherwise reliable senses such as thermoception (hot/cold) and nociception (pain) which they would naturally depend on to avoid damage to the skin/suit. This leaves the EVA suit vulnerable to contact with surfaces subject to sudden changes in temperature or other damaging effects that may go unnoticed by an operator with no form of feedback.
The second example is with prosthetic hands. Prosthetic hands are another concern because they currently lack any sensory feedback whatsoever. A simple task such as holding an object that would normally require one hand now necessitates both hands and significant directed visual attention on the object being held to make sure it does not slip. Most users of prosthetics would like to have sensory feedback incorporated into their prosthetic to prevent the need for this high degree of visual vigilance (Pylatiuk, et. al, 2009). When prosthetic users were surveyed, 88% reported feedback was important to the use of the prosthetic while 45% reported it was “absolutely important” (Lewis, et. al, 2012). Touch naturally provides necessary sensory feedback in grasping tasks in order to unconsciously upgrade and maintain appropriate grip forces via mechanically sensitive organs embedded in the skin known as mechanoreceptors. Both electrical and mechanical skin stimulation to the residual limb can increase the performance in controlling the prosthetic and the user’s acceptance of a prosthetic hand (Panarese, et. al, 2009).

Touch is also essential in gathering information about an object via a haptic glance (Klatzky and Lederman, 1995) -- the initial and primary means of perceiving somatosensory information. The haptic glance is critical in object recognition, as well as determining manipulatory posture and maintaining a stable grasp. Proper grasping is fundamental for the performance of any basic manual task for maintaining control over the object and removing the need for constant visual attention.

In both examples, when the tactile sense is impaired or missing, clearly errors and risk of harm will increase. The tactile information needed for better performance can be conveyed through feedback in any of the sensory modalities, such as vision, audition or touch (including
at a remote [different] location than where it is sensed and in a different format). For touch, consideration of a different format (e.g., vibration for grasp force or vibration for temperature) is desirable: actuators that can apply forces (versus vibration) are costly, heavy and power hungry and devices (such as Peltier systems) that can portray temperature have slow response times. Vibration feedback is desirable as it can be made with small, low cost vibrators that are commonly found in smartphones (such as linear resonant actuators). Linear resonant actuators (or LRAs) have a quick response time as well.

One may propose to use visual or auditory feedback, as these modalities have a large set of affordable and sophisticated commercially developed displays. However, another issue that should be considered is cognitive load. It is posited that each of the sensory modalities have their own working memory (Samman and Stanney, 2006). Vision and audition, during these tasks, are normally sensing important task relevant information in their domains: an additional display in their modality as a substitution for touch would place a burden on their finite working memory. However, with no direct external feedback available for touch to sense, a large amount of its working memory is available to process additional information. In a study comparing feedback modalities during a motor task in which subjects used a computer mouse to quickly click a target on a computer screen, the tactile feedback condition yielded quicker motor response than both the auditory and visual feedback conditions, with no effect on accuracy (Akamastu, et. al 1995).

The research question being asked in this thesis is whether the location at which vibrotactile feedback is applied to assist with sensing and manual manipulation affects the ability of the user to perform a task. Performance is defined in terms of successful completion
of the task, accuracy of task performance and/or speed of task completion. The hypothesis is that the closer the feedback site is to the site of action, the better the performance, with best performance being when feedback and action are co-located at the same site. The basis for this hypothesis is that using conscious feedback for manipulation is difficult to begin with, the cognitive load of a person is thought to be finite, and anything increasing this difficulty, such as possibly increasing the separation, either in time or space, between the site of activity and the site of feedback, is likely to affect performance. It is also possible that other factors such as site sensitivity may have an effect.

1.2 Organization of Thesis

The remainder of the thesis is organized into five sections: Study Design Considerations, Methods, Results, Discussion and Conclusion. The first section takes into consideration the different aspects of the problem and possible solutions. It will first consider the known physiology and psychophysics characterizing the body sites and tasks being considered for feedback. Then it will further consider applicable hardware and signal generation.

In each of the Methods, Results and Discussion sections we will first describe pilot work performed to determine an effective vibration parameter for conveying information. We will particularly focus on parameters that can produce variations in roughness, which is a much easier concept for naive users to grasp than specific waveform parameters. Second, we will describe an experiment (referred to as the Pipes Decision Experiment) where users are required to determine if it is safe to connect two pipes (one in each hand) together. Both whether the response which occurred was correct and the response time will be analyzed. Third, we will describe an experiment (referred to as the Wrench Gripping Experiment) where users are
required to apply an appropriate grip force to a wrench based on vibratory feedback about the virtual frictional properties of that surface. Both the response time and steady state error will be analyzed.

Finally, we will describe implications for general design considerations in the Discussion section.

2. Study Design Considerations

To make appropriate design decisions in relaying information through mechanical vibration of the skin it is important that we take into consideration an understanding of the physiological and psychological properties of mechanoreception in the skin, hardware alternatives and effects of signal choice.

2.1 Mechanoreceptors in glabrous versus hairy skin

Thousands of mechanoreceptive units are found on the glabrous (non-hairy) and hairy skin of the body. The mechanoreceptors in the glabrous skin of the hand have been categorized by two properties: the size of their receptive fields (Type I is small and Type II is large) and how they respond to a constant level mechanical indentation (SA or Slowly Adapting units respond both at onset/offset and during the sustained portion, FA or Fast Adapting respond only at onset and offset). For a grasp and lift task, Johansson and his colleagues (e.g., Johansson and Flanagan, 2007) found that the FA II units respond when the object is lifted off the table and set back onto it; whereas, the other types of receptors (FA I, SA I, SA II) seem to signal the initial contact and final release of the fingers from the object, direction of the contact force, frictional information and local curvature. In addition, the glabrous skin has two types of
thermoreceptors, known as warm and cold receptors, and nociceptors responding to pain. (Jones and Lederman, 2006).

In contrast, hairy skin areas (such as on the back of the hand or arm) have no FA I mechanoreceptors and a predominance of SA receptors (Johansson and Flanagan, 2007). Edin has suggested that, at least on the back of the hand, the receptors play a proprioceptive role in determining hand configuration (Edin, 1992). Mechanoreceptors are found in hairy skin either in touch domes or associated with the hairs. The receptors associated with the touch domes are SA type receptors, with multiple end organs of a single nerve fiber located beneath each dome. FA I receptors are frequently found associated with hair follicles along with other receptors, such as those responding to pain (Orime et al., 2013).

A meta-analysis of studies involving sensory feedback in prosthetics (Antfolk, et. al) show upper arm, forearm, and residual limbs of both transradial and upper arm amputees to be the most widely accepted and effective location for feedback due in part to glabrous skin. Feedback at these locations were reported to improve precision and accuracy of positioning tasks with prosthetics, precision and lower error rates in grasp force, and increased user satisfaction.

2.2 Vibration sensitivity as a function of body site

Although the actual tactile feedback to the fingertips for grasping and manipulation is very rich: providing both constant force levels and vibrations, and varying in spatial-temporal detail across the fingertip, current technology is not able to replicate this information at a remote site. Relatively simple, single point vibratory signals seem to be the most practical given their cost, energy expenditure and engagement of consciousness in assisting with the tactile component of manual tasks.
Vibrotactile threshold values are lowest at the fingertip which is also the location of the highest density of mechanoreceptors, most notably SA I and FA II (Vallbo & Johansson, 1984). Locations such as the calf and mouth are more sensitive than the upper arm in the absolute threshold of high frequency vibrations, but would be less practical feedback locations during manual tasks. Sensitivity at the shoulder is comparable to the upper arm, but was not chosen due to the commonality of transhumeral amputations providing a prime feedback location on the upper arm. The body sites that were selected for study were: the fingertip of the index finger, the ventral surface of the forearm and the ventral surface located above the bicep.

However, work comparing threshold values of the fingertip and forearm (Jones & Sarter, 2008) show a larger physical amplitude is needed on the forearm and abdomen than the finger pad to produce the same perceptual intensity for identical frequencies. This suggests that when comparing sites, it might be more appropriate to compare the vibration feedback for constant levels of perceived magnitude, rather than physical magnitude. It is also the relevant parameter that is utilized in interpreting any information by the user. This is particularly important if scalar parameters need to be conveyed. Scalar parameters are defined here to mean parameters that are to be used quantitatively: for example, “2” added to “10” or “90” conveys the same perceptual difference.

In addition, both physical amplitude and frequency of vibrotactile signals interact to produce a perceptual amplitude to the user. This effect also needs to be accounted for if the display parameter of amplitude or frequency is to be used quantitatively. Verrillo (1969) demonstrated the effect frequency has on the perceived amplitude of vibrotactile stimulation on the fingertip: Lower frequencies have a higher threshold, while higher frequencies have a
lower threshold. The lowest threshold is at 250 Hz, which is the peak sensitivity of the Pacinian corpuscles. Threshold at the forearm also was shown to have a similar relationship to frequency as threshold on the finger pad (Jones & Sarter, 2008). Other display parameters are known to interact, but their interaction has not been studied.

2.3 Task Considerations

It is not sufficient to only examine the perceptual response of the tactile system to vibratory input at the different potential locations for vibration feedback in comparison to on the hand. It is also important to determine whether this information can be used effectively in practical tasks. The two tasks that will be considered in this thesis are: (a) the decision as to whether two pieces of pipe, which may each be at any temperature, can be safely joined together, and (b) grasping objects of varying frictional coefficients between the thumb and forefinger.

For both tasks, the loss of the tactile sense removes the ability to gather important information about the environment and respond appropriately (Klatzky & Lederman, 1995; Johansson and Flanagan, 2007). This includes the normal reflex arc pain response to hot surfaces as in the first task example. Although the threshold may be higher with protective gear or a prosthesis, protection can be critical: for example, the life and death situation of a puncture in a space suit. In addition, thermal properties of an object are among the most highly salient diagnostic properties of touch (Klatzky and Lederman, 1995) and are important in a variety of (space) tasks. For example, one relatively common task for astronauts is fixing broken pipes. A key aspect of the task is determining whether the two pieces of pipe to be joined are relatively the same temperature. Otherwise, the pipe joint may be rebroken when
the two pieces become thermally balanced. In addition, it is possible that one or both pipes are too hot to be handled without damaging the space suit. In this thesis we will consider the ability of the users to determine whether two pieces of pipe can be joined together.

For prosthesis, perhaps the most basic of tasks to be performed is to grasp and lift an object. Johansson and Westling (1984) determined that there are two main mechanisms at work to maintain grasp stability for an upright object between the thumb and forefinger of a healthy human hand. The objective of these mechanisms appears to be to prevent the object from slipping while at the same time ensuring the forces used do not become excessive. Although a motor driving a prosthetic will not get “tired”, using excessive forces will result in a significantly shorter battery life. In addition, if an object is fragile, it may be broken if excessive forces are used. Johansson and his colleagues found that people adjust their grasp force in response to the (predicted and current) load force based on the response of mechanoreceptors to information obtained through the senses about friction and object shape (Johansson and Flanagan, 2007). The second task we will use is to ask the users to adjust their grip force (based on vibrational feedback that we will provide) as if responding to changes in friction.

2.4 Hardware Consideration

Most devices employed to provide remote tactile feedback are categorized as either vibrotactile (mechanical) or electrotactile (or electrocutaneous). Devices to produce static indentation are possible but are generally expensive, bulky and power hungry: three undesirable qualities of a wearable device. While electrotactile devices consume less power than vibrotactile devices, vibrotactile stimulation is considered superior in discriminability and ability to stimulate the appropriate mechanoreceptors involved (Ciancio & Cordella, 2016).
Vibrotactile feedback is also considered more comfortable to many users. Electrotactile feedback has been qualitatively described as vibration, but also undesirably as a pinch, prickly or a sharp and burning pain depending on the voltage. In addition, changes in perception can occur with variations in electrical impedance of the skin and subcutaneous tissue through sweating or hydration (Pawluk, Adams and Kitada, 2015). Pain thresholds for electrotactile stimulation also vary between individuals and require sweat to build up or applying a gel to avoid prickly sensations. Vibrotactile stimulation may only cause pain if the device generates heat greater than 62 mW/cm² (Kaczmarek, 1991).

Both DC motors and linear resonant actuators (LRAs) can be used as tactors. DC motors include eccentric rotating mass (ERM) motors with frequencies dependent on voltage amplitude which supply a dynamic response (vibration) and linear solenoid actuators which supply a static response (indentation). LRAs are controlled with AC current and have a resonance frequency at which peak amplitudes are exhibited. Some linear actuators have a very narrow frequency response such as the C10-100 (Precision Microdrives) which will not produce salient signals too far outside its peak value of 250 Hz. In contrast, the C3 tactor (Engineering Acoustics) has a resonance frequency at 250 Hz and can operate in the frequency range of 180 to 320 Hz (Engineering Acoustics website, 2017). The C3 is also capable of much stronger vibrations.

2.5 Signal Consideration
Signal design should consider the perceptual abilities of human users, the tasks described, and the common hardware used in vibrotactile feedback systems as reviewed above. Signals should be well above threshold values but not too high: Signals too weak will require cognitive
effort just to detect, while signals too high could cause pain. The individual signals within the set used for feedback must also be reliably and easily discriminable from one another so as not to contribute to the cognitive load. Two further issues are that, as with other sensory systems, perceptual values are not equal to physical values and the perceptual parameters interact (as described earlier).

Potential waveform parameters that have been previously used in our laboratory and by others are: perceived magnitude, frequency, amplitude modulation (AM) frequency and waveform shape (Burch and Pawluk, 2011). Although these parameters are clear to a designer, they are less clear to most users. This is an important consideration when presenting scalar rather than nominal dimensions (i.e., the latter only needs to feel different, not convey information about amount/how different). However, feedback signals can also be perceived in terms of more haptically relevant descriptions, such as roughness. Roughness has been studied extensively in the psychophysical literature (Lederman, 1974). Its rendition in virtual reality has also been considered extensively. Several research groups have modeled roughness in terms of sine waves of varying spatial period. In some of these papers, the signal was rendered directly on a single tip as a corresponding temporal sine wave. Others, took probe geometry into account. Headley and Pawluk (2011) examined the variation of ridge width and groove width of square waves as well, in keeping with previous psychophysical experiments with physical gratings by Lederman and her colleagues.

Any waveform parameter must be able to represent a scalar dimension for conveying quantitative information necessary for a task. This means that its perception, whether directly or by an analogy such as roughness, is most desirably a function that increases (or decreases)
monotonically with constant (linear) slope. This allows for a simple relationship between the information conveyed and the perceived quantity. Deviations from this objective are likely to increase cognitive load and/or reduce performance by adding the difficulty of interpreting the parameter cue. Increasing/decreasing monotonicity is important as otherwise one has a many-to-one mapping between the information to be conveyed and the display parameter. Of relevance are previous results that have found that roughness can be described, with some parameters, as an inverted U-shape or a constant value at lower spatial periods/temporal frequencies. Similar issues could exist for other parameters and may also vary between different body sites.

Choosing a signal parameter should also take into consideration the limits of the hardware chosen. For example, linear resonant actuators (LRAs) only have significant deflection at their resonant frequency. Therefore, using frequency as parameter is not appropriate; although manipulating the frequency of amplitude modulation (AM) is appropriate. Other parameters, such as the time duration of a vibration or playing a unique tactile “tune” require a finite time to completion that could introduce unacceptable delay in the system, particularly when considering dynamic grasping and manipulating tasks.
This thesis explores a variety of different potential signals. It focuses on the manipulation of the modulation frequency of an amplitude modulated (AM) signal. The waveforms generated kept a constant carrier frequency of 250 Hz, which corresponds to the most sensitive peak of tactile perception. Based on previous work in our laboratory (Burch and Pawluk, 2011) 30-dB SL will be used at all sites. Modulation frequency will be manipulated on a log scale as distances, at least for pure sine waves, on this scale relate linearly to distances in perception.

3. Methods

3.1 Perceptual Experiments

3.1.1 Apparatus and Stimuli
The experiment was performed with a C3 tactor (Engineering Acoustics) providing vibrotactile signals while secured to each subject’s second digit finger pad, forearm or bicep. These sites correspond to the direct co-location of the feedback with the finger performing the task, approximate placement of myoelectric control for transradial prostheses and approximate placement of myoelectric control for transhumeral prostheses, respectively. For the finger, the
tactor was mounted inside of a plastic ring that fit around the finger with an aperture for the contactor to stimulate the skin on the finger pad. For the other two sites, an approximately 4-inch-long fabric cuff made of a stretchable nylon type fiber was provided to secure the tactor just below the elbow joint at the midline of the forearm or just above the elbow joint at the midline of the bicep. In all cases the tactor was secure against the skin but without a significant pre-indent. Signals were provided to the tactor by a LabVIEW data acquisition system (DAQ) and amplified by a current amplifying circuit.

Subjects wore headphones while listening to pink noise to prevent sounds from the tactor from influencing discrimination between signals.

3.1.2 Exploration of parameter discrimination pilot experiments

The use of a C3 tactor was necessary as a tactor strong enough to excite the area of skin at the bicep was needed, which is much less sensitive to the finger pad. A variety of stimulus dimensions were examined as a mapping from the information domain (i.e., either temperature or grip force) to the perceptual domain.

We began to systematically test the ability to discriminate between individual signal parameters on the finger pad. Each pilot presented 4 subjects with multiple pairs of signals with a parameter to discriminate between while all other parameters were kept constant. E.g. Study 1 was a discrimination task between two signals with the same frequency, but at different amplitudes and was repeated for multiple pairs of amplitudes (Table 1).
Table 1: Pilot Studies for discriminating between certain waveform parameters within other waveform parameters.

<table>
<thead>
<tr>
<th>Study No.</th>
<th>Discrimination Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameter discriminating between</td>
</tr>
<tr>
<td>1</td>
<td>Sine wave amplitudes – 0.25, 0.5, 1.0, 2.0 volts</td>
</tr>
<tr>
<td>2</td>
<td>Square wave amplitudes – 0.25, 0.5, 1.0, 2.0 volts</td>
</tr>
<tr>
<td>3</td>
<td>AM frequencies (amplitude balanced) – 100, 40, 24, 12, 0 Hz</td>
</tr>
<tr>
<td>4</td>
<td>AM envelope waveform shape (amplitude balanced) – Sine, Square</td>
</tr>
<tr>
<td>5</td>
<td>Frequency-Amplitude Relationship – 12, 24, 40, 100 Hz &amp; 0.25, 0.50, 1.0, 2.0 volts</td>
</tr>
</tbody>
</table>

The signal pairs were presented and the voltage of one of the signals was increased or decreased until the subject could say they were equally intense (the amplitudes were perceived to be equal). This was done to insure the subject would be discriminating between one parameter, such as frequency, and not a combination of frequency and amplitude.

Then subjects were repeatedly presented two signals in a row and asked to discriminate by answering if they were the same or different. An equal number of same and different pairs were presented in random order for a total of 24 trials.

Based on the discriminability results of these pilot experiments, the value of the carrier frequency of amplitude modulation was chosen as the parameter onto which the desired information parameter should be mapped. To be used as a scalar dimension, the mapping from the information parameter to perceived variation in amplitude modulation needs to be linear (i.e., related through a numeric gain and offset). Although in different situations we may want to use a different dimension from the environment (e.g., temperature or grip force), if these are mapped linearly onto a common display dimension (e.g., roughness) and this dimension is
linear with variation of the carrier frequency of amplitude modulation then it can be used as a scalar dimension. Fortunately, the percept due to varying the carrier frequency has been described as “roughness” (Hoggan and Brewster, 2007) which also makes the display parameter more accessible to non-engineers who may not be familiar with AM. We therefore need to determine if roughness is indeed linear with variations in carrier frequency at the three different upper arm sites.

3.1.3 Participants

There were 4 participants for pilot discrimination experiments and 8 participants for the final equal sensation level and roughness magnitude estimation experiments. Subjects were recruited from a population of convenience, and consisted of undergraduate and graduate students recruited from VCU School of Engineering, aged 20-30. There were 4 males and 4 females. All subjects had full sensation and unimpaired dexterity in their hands. IRB approval was obtained for this experiment.

3.1.4 Experimental Design

To determine the relationship between variations in carrier frequency and perceived roughness at the three different upper arm sites (finger pad of index finger, forearm and bicep), a two-step process was used. The first step was based on the expectation that perceived magnitude would vary as a function of the carrier frequency analogous to results obtained with varying the frequency of pure sine waves. To ensure we did not confound perceived magnitude with perceived variations due to carrier frequency, we first performed a similar experiment to Verrillo (1969) to determine equal sensation levels. The equal sensation level (SL) that was chosen was 30 dB SL as it was significantly above threshold and easily detected without being
irritating. The second part of the process was to determine the perception of roughness as a function of carrier frequency at the 30 dB SL.

To obtain the equal sensation levels for AM signals we used a similar study design to Verrillo (1969) except we varied the carrier frequency of an AM signal rather than the frequency of a pure sinusoid. For the AM signal, the base frequency was kept constant as a 250 Hz sine wave, while the varied carrier wave was a square wave. Two reference signals (high and low) were used to match test signals, which were 250 and 64 Hz. Instead of a direct matching procedure as in Verrillo, 1969 in which subjects adjusted the signal intensities themselves, a modified staircase method with preset termination criteria was used and is explained below.

The modified binary search technique (MOBS,) was used to determine equal sensation level (SL) for the set of vibrotactile signals. This was because it is more efficient and less susceptible to response errors than traditional staircase procedures at the cost of increased testing time (Tyrrell and Owens, 1988). Each vibrotactile signal was applied with the C3 tactor to each testing location followed by a reference signal. Subjects were asked to indicate whether the test signal was higher or lower in intensity than the reference until the binary search algorithm reached its termination criteria. The MOBs procedure is presented below:

1. The test range is defined by two boundaries consisting of a three element “stack”. The top element in either stack gives the current top and bottom boundary value, with lower elements giving earlier boundary values. All elements in the low stack are initially set to the minimum signal intensity and all elements in the high stack set to the maximum intensity.

2. The signal intensity presented to the subject is always midway between the top element of the high and low stacks.

3. If a subject sees (or in this case feels) the signal, each element in the high stack is moved down by one, losing the bottom element as the current signal is placed in the top
element. If a subject fails to feel the signal, each element in the low stack is adjusted in the same manner.

4. If two consecutive “seen” responses are given, the top element of the low stack is presented. If two consecutive “unseen” responses are given, the top element of the high stack is presented. If the response to either of these top element signals is inconsistent with the last time that signal was presented, the stack undergoes a regression.

5. A stack undergoes a regression by moving all elements up by one (losing the top element in the process).

6. The procedure continues until two criteria are met: a predetermined number of reversals occur (usually 4-6) and the difference between the current signal and previous signal at the final reversal is less than 5% of the test range, otherwise 2 additional reversals are required.

   For the second step, roughness perception at the 3 arm sites, subjects were told the signals presented could be interpreted as varied levels of roughness and compared to qualitative references such as silk (not rough), suede (rougher), and sandpaper (very rough). Silk was associated with the lowest end of the rating scale starting at zero, while 100 was associated with the roughest grit sandpaper. All signals were presented in random order to allow subjects to consider how they may be ranked against each other before reporting subjective values on the scale.

   This procedure was performed for all three locations: finger pad, forearm and bicep and was counterbalanced across subjects.

3.1.5 Experimental Procedure

   Subjects were asked to seat comfortably at a table with the experimental apparatus in front of them. Subjects were presented the reference signals and were asked if they could perceive it until MOBS met its termination criteria. When comparing test signals to the
reference signals, subjects were asked if the first signal was more intense or less intense than the second until mobs met its termination criteria.

Subjects were also asked to rank each signal on how rough the signal felt at each location from 1 (very smooth) to 100 (very rough). The set of 6 30dB SL signals were presented in random order eight times and the responses were averaged together

3.1.6 Experimental Analysis
The subject data was averaged together for plotting both the Equal Sensation Level (SL) curve and the roughness magnitude estimation (RME) curve for each location. The equal SL values were needed to remove perceived amplitude from being a discriminable factor between the signals. The 30dB values and the relationship between perceived roughness and frequency from the RME were used to determine the signal set used in each experiment. The range of AM frequencies (0 to 124 Hz) derived from the plot was scaled to fit the range of simulated temperatures in the Pipe Decision Experiment and the range of load ratios in the Wrench Gripping Experiment

3.2 Pipe Decision Experiment

3.2.1 Apparatus and Stimuli
To simulate the condition in which a user must decide whether two pieces of pipe are sufficiently comparable in temperature that they can be joined, a male-female pair of threaded PVC pipe were used that had a 1.5” outer diameter and was approximately 12” long. The male pipe was fixed on one end in mid-air and the length was oriented tangentially to the user on a table. The female pipe was screwed halfway into the male pipe (Figure 1). For this experiment,
two tactors were used; one secured on the left upper limb and the other secured on the right upper limb, as described in the Perceptual Experiments. The tactor placed on the left upper limb was used to indicate the temperature of the male pipe (on the left of the subject). The one placed on the right upper limb was used to indicate the temperature of the female pipe (on the right of the subject). Testing occurred with tactors at the two index finger pads together, the two forearms together and over the two biceps. Signals were provided to the tactors by a LabVIEW data acquisition system (DAQ) and amplified by a current amplifying circuit.

Figure 2: Pipes Decision Experimental Apparatus

3.2.2 Participants
Subjects were recruited from a population of convenience, and consisted of undergraduate and graduate students recruited from VCU School of Engineering, aged 18-30.
There were 3 males and 5 females. All subjects had full sensation and unimpaired dexterity in their hands. IRB approval was obtained for this experiment.

3.2.3 Experimental Design

The study variables consisted only of within subject factors: upper limb location (3), reference temperature (3), hand reference temperature applied to (2), magnitude of temperature deviation from the reference (potentially 6), and block number. The upper limb locations were the same as for the perceptual experiment: second digit finger pad, upper forearm and bicep. The reference temperatures were: 0, 80 and 160 degrees. A discrepancy between the pipes of 40 degrees or greater was considered too large to proceed with the task. Therefore, the four possible deviations from a reference chosen were: +30 and +50. However, trials that contained temperature values less than 0 or greater than 160 degrees were not included in the experiment.

The additional two temperature deviations from the reference were the cases in which the temperature at the reference or the comparison, respectively, was too hot to handle. This was handled by the special case of no amplitude modulation (i.e., only the base frequency of 250 Hz at 2.0 volts amplitude), which participants felt as qualitatively different from the other signals. The hand choices for the presentation of the reference temperature was either left or right.

The number of blocks and participants were chosen to obtain a targeted statistical power of 0.9. Glimmpse, the online power and sample size analysis engine (http://glimmpse.samplesizeshop.org/#/), was used to determine these values, based on the other variables and the variance of the data from the pilot studies. From the analysis, 5 blocks
of 10 trials each were needed to allow for a study population of 8. For the study, location was counterbalanced across participant. Within each block, the 10 trials were drawn from the set described by the parameters in the previous paragraph without replacement.

The temperature values then had to be mapped onto a scalar dimension of touch that could be represented by vibration. We chose roughness as it is one that is intuitive as compared to more specific physical parameters (such as amplitude modulation) which may be unfamiliar to non-engineers. In addition, physical parameters do not map 1:1 onto perceptual parameters, so manipulation of a single physical parameter is less than ideal. The methodology of how this conversion was made is described in the results section as it is dependent on the outcome of the perceptual experiments.

3.2.4 Experimental Procedure

Participants were asked to stand in front of the experimental apparatus in front of them. First the purpose of the task was explained to the users: they would be given the percept of roughness the use of vibration signals on both their left and right sides, and had to decide if: (a) the pair of pipes was safe to put together, (b) the pair of pipes was not safe to put together, or (c) one or more of the pipes was “too hot to touch”. They were also instructed to start each trial with their respective hands resting about an inch above each of the left and right pipes. If the pipes were safe to put together, they were to start screwing them together. If the pipes were not safe to put together, they were to pull their hands away. If one or more of the pipes were “too hot to touch”, they were to pull their hands away as rapidly as possible. Both the response and the response time were to be recorded.
Participants were then trained to do the task with reference values of 40 and 120 degrees. The values chosen were purposefully different than the reference values for testing as in testing, the intention was to see how well participants could generalize what they learned to the entire temperature scale. However, similar deviations were used (+30, + 50 degrees, plus “too hot”) as the 40-degree temperature difference which defines the point at which the task cannot be completed needed to be learned. Participants were trained with verbal feedback and continued until their response rate was 60% for 3 blocks in a row.

Participants were then tested with reference values of 0, 80 and 160. They were told that the temperature/roughness values that they will feel will be different than in training, but that the deviations indicating whether it is safe to screw the pipes together or not will be the same.

3.2.5 Experimental Analysis

Generalized estimated equations were used in SPSS to model the outcome of the correctness of the response and the response time. The outcome of the correct response was modeled by a binary logistic function, as the response was either correct or incorrect. The outcome of the response time was modeled as a Poisson distribution, as time distributions typically take on this form and our data indicated as much. Both models included main effects of: Block (1-5), Location (finger pad, forearm, bicep), Reference (0, 80 or 160), Reference Hand (left or right) and Difference +30 degrees, + 50 degrees, or too hot, and all two-way interactions. A compound symmetric matrix was chosen as the correlation matrix because we expected correlation between repeated measures (i.e., responses from a given subject over all conditions not expected to be independent [Hanley et al., 2003]). For each model, following
standard procedure, after the analysis, only the terms that were statistically significant, and, in the case of interaction terms, both main effects were significant, were included in the final model.

3.2 Wrench Gripping Experiment

3.3.1 Apparatus and Stimuli
A test object in the shape of a common hand tool (socket wrench) was produced using a rapid prototyping machine (Makerbot 3D printer) with extensions made to accommodate two load cells (Figure 2). A beam load cell (CZL635 Phidgets, Inc) with a sensitivity of 1 mV/V and resolution of 5g/bit was placed cantilevered on top of the test object attached to a plastic extension such that when placed in a pinch grip, the weight of the object would be equidistant from either finger. A compression load sensor (FS20 -TE Connectivity, Ltd.) with a resolution of 0.5/bit was adhered to one end of the beam load cell where the subjects thumb would be placed. Both load cells were wired to an Arduino Uno microprocessor (10-bit ADC) with a strain gauge shield add-on. The Arduino was connected to a PC running MATLAB which collected the raw data in terms of the load and the grip force. MATLAB was then used to compute the load ratio, which was displayed as a real-time plot, and saved the data for analysis.

Vibrotactile stimuli were provided to a C3 tactor via a LabVIEW DAQ in a similar manner as in the previous experiment, but only to a single tactor on the same side as the hand which held the wrench. Johannson and Westling found the resulting ratio between grip force of the finger and load force of the object was smaller for rougher surfaces and larger for smooth ones. Therefore, this time the roughness signal acted as a proxy for the ratio between the load and grip forces. The tactor was secured to the upper limb in the same manner as described in
the Perceptual Experiments, except for the finger pad condition where the tactor was placed inside a glove (Figure 2). The tactor ring interfered with grip application, so the C3 was placed inside the glove instead so the subject had a more natural grip and did not compress the tactor between their finger and the sensor which would have damped the signal. Gloves also help simulate tasks requiring protective equipment.

Figure 3: C3 Tactor and Glove for Wrench experiment (Left) and the test object (Right) for the Wrench experiment with sensors labeled: (1) beam load cell and (2) compression load cell

3.3.2 Participants
Subjects were recruited from a population of convenience, and consisted of undergraduate and graduate students recruited from VCU School of Engineering, aged 18-30.
There were 3 males and 4 females. All subjects had full sensation and unimpaired dexterity in their hands. IRB approval was obtained for this experiment.

3.3.3 Experimental Design
The study variables consisted only of within subject factors: upper limb location (3), target steady state grip to load force ratio to avoid slipping (3), block number and trial number within block. The upper limb locations were the same as for two previous experiments: second digit finger pad, upper forearm and bicep. The target steady state ratios were 1, 2.5, and 4.

The number of trials, blocks and participants were chosen to obtain a targeted statistical power of 0.9. Again, Glimmpse was used to determine these values. 6 blocks of 3 trials were needed for a study population of 6 (7 were used). Location was counterbalanced across participants. The 3 trials of each block consisted of the 3 target steady state ratios in random order.

Load ratio cues had to be mapped onto a scalar dimension of touch that could also be represented by a vibration motor. Again, like in the previous experiment, roughness was chosen as it is an intuitive parameter with the addition of being much more relatable to the task at hand as surface roughness is proportional to the amount of grip force necessary to lift an object. The same methodology was used as in the Pipes experiment and is described in the results section of the perceptual experiments.

3.3.4 Experimental Procedure
Participants were asked to seat comfortably at a table with the experimental apparatus in front of them and their elbow supported by the armchair. First the task was explained to the participants: they would grip the test object between their thumb and 3rd digit (middle finger)
in response to perceived roughness produced by vibrations which would indicate varied levels of force application. Then participants were asked to familiarize themselves with the device such that they found a comfortable elbow support, to limit fatigue, and finger position for gripping the sensor effectively.

Participants were trained to apply a grip force to achieve steady state load ratios of 1.75 and 3.25 by watching a real-time plot of sensor data on a computer screen. Values different than those for testing were used as we were interested in determining how well participants could generalize to the entire scale when testing, without having to test the entire scale. Participants were trained with verbal feedback and continued until their response rate was 60% for 3 blocks in a row.

Participants were tested on target steady state ratios of 1, 2.5 and 4. They were told the two training signals would be swapped for three testing signals that should feel as far apart in the perceived degree of roughness as the two test signals. For each trial, subjects waited while applying a slight preload on the sensor and were asked to upgrade their grip force as quickly and accurately as possible.

3.3.5 Experimental Analysis

Raw force sensor data was smoothed with an averaging filter to remove noise from the signal. Signal responses were divided up from the onset of the vibrotactile signal to the end of steady state grip when the subject released their hand from the wrench. A second order differential equation was constructed to fit each isolated force ratio waveform response to the target ratio signal to determine steady state values and time constants using a custom MATLAB script using the ode45 function.
Figure 4: Experimental Data fitted with an ordinary differential equation. The circle denotes time constant and the square denotes settling time.

Generalized estimated equations were used in SPSS to model the outcome of the steady state ratio error, time constants of the fitted second order differential equations and response time. The outcome of the steady state error was intended to be modeled by a Normal distribution with an identity link function. The outcomes of the time constant and response time were modeled as Poisson distributions, as the data again took this form as time distributions typically do. All models included main effects of: Block (1-6), Location (finger pad, forearm, bicep), and target steady state ratio (1, 2.5, 4) and all two-way interactions. A
compound symmetric matrix was chosen as the correlation matrix because we expected correlation between repeated measures. For each model, following standard procedure, after the analysis, only the terms that were statistically significant, and, in the case of interaction terms, both main effects were significant, were included in the final model.

4. Results

4.1 Perceptual Experiments
In pilot studies (Table 2) the ability to discriminate equal sensation levels (SL) AM frequencies proved to be better than the ability to discriminate amplitudes, pure sinusoidal frequencies and carrier waveform shape. Co-varying and inversely varying amplitude modulation frequencies with amplitude yielded marginally larger A’ values. However, the perception of the amplitude values used were physical quantities that were dependent on the transfer function of the motor used and human perception to give the amplitude dimension actually perceived. In addition, AM frequency, by itself, can be related to an intuitive description of a physical quality perceived by touch -- roughness.

4.1.1 Pilot Results
Table 2: Values of sensitivity from discrimination pilot testing.

<table>
<thead>
<tr>
<th>Study No.</th>
<th>Discrimination Parameters</th>
<th>Average d'</th>
<th>Average A'</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sine wave amplitudes (volts)</td>
<td>2.134</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>Square wave amplitudes (volts)</td>
<td>1.915</td>
<td>0.87</td>
</tr>
<tr>
<td>3</td>
<td>Sine wave AM frequencies</td>
<td>2.88</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Square wave AM frequencies</td>
<td>2.46</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>AM envelope waveform shape (sine vs. square)</td>
<td>1.23</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>Co-varied Frequency-Amplitude Relationship</td>
<td>3.01</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Inversely varied Frequency-Amplitude Relationship</td>
<td>3.01</td>
<td>0.97</td>
</tr>
</tbody>
</table>

4.1.2 Equal Sensation Level Curves

In Figure 3 the 30dB equal sensation levels of each location to the signal set are compared and plotted on log scale. The finger pad is the most sensitive and is the most uniformly sensitive across the frequency range out of all locations. The forearm and bicep have similarly shaped 30dB curves, however the forearm is much more sensitive to lower frequencies, similar to the finger pad. High frequency detecting mechanoreceptors are concentrated more densely in the finger pads, which explains the disparate levels of sensitivities at higher frequencies between the finger pad and locations farther up the arm. The bicep is notably more insensitive at high frequencies compared to both other locations.
Figure 5: 30 dB equal sensation level curves for the finger pad (blue), forearm (yellow), and bicep (red). Values for pure sine wave are seen as circles in purple. The amplitude of the AM signal is plotted against the log of carrier wave frequency.

4.1.3 Roughness Magnitude Estimation

The perceived magnitudes of the waveforms were equalized to ensure that we only were manipulating the modulation frequency and then correlated with roughness. For frequencies above 25 Hz, the perceived roughness appears to decrease relatively linearly as a function of modulation frequency at all three sites. For the mean roughness perception as a function of modulation frequency at the different sites, a line was fit to the data for frequencies greater than and equal to 24 Hz using the function polyfit in MATLAB. The slopes and y-
The intercept values were, respectively: -0.3810, 71.2372 for the finger, -0.3398, 58.6038 for the forearm and -3619, 65.6678 for the bicep.

Figure 6: Individual subject traces for roughness magnitude estimations at each location. Finger pad (Upper left), Forearm (Upper right), and Bicep (Bottom)
Figure 7: Mean values of Roughness Magnitude Estimations for finger pad (solid, red), forearm (dotted, green), and bicep (dashed, blue).

4.1.4 Roughness Scalar Dimension Mapping

The average subjective roughness magnitude values were scaled to the testing range of simulated temperatures or target force ratio by a factor equal to the ratio of the dimension
ranges. The linear region of the RME curve, which begins at some initial peak frequency ($I$), was isolated and curve fitted for its slope ($m$). Thus, the formula to map the roughness dimension onto one of the testing dimensions becomes:

$$AM(i) = I + m \times \text{temperatures}(i)$$

$$AM(i) = I + m \times \text{ratios}(i)$$

Table 3: Derived scalar values for the temperature range in the Pipes Decision experiment

<table>
<thead>
<tr>
<th>Signal No.</th>
<th>Temperature</th>
<th>AM Frequency (Hz)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Finger pad</td>
<td>Forearm</td>
<td>Bicep</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>25.00</td>
<td>6.00</td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>32.70</td>
<td>13.32</td>
<td>12.19</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>40.40</td>
<td>20.64</td>
<td>18.37</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>48.10</td>
<td>27.96</td>
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<td>40</td>
<td>55.80</td>
<td>35.28</td>
<td>30.75</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>50</td>
<td>63.50</td>
<td>42.60</td>
<td>36.94</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>60</td>
<td>71.20</td>
<td>49.92</td>
<td>43.12</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>78.90</td>
<td>57.24</td>
<td>49.31</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>80</td>
<td>86.60</td>
<td>64.56</td>
<td>55.50</td>
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<tr>
<td>10</td>
<td>90</td>
<td>94.30</td>
<td>71.88</td>
<td>61.68</td>
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</tr>
<tr>
<td>11</td>
<td>100</td>
<td>102.00</td>
<td>79.20</td>
<td>67.87</td>
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</tr>
<tr>
<td>12</td>
<td>110</td>
<td>109.70</td>
<td>86.52</td>
<td>74.06</td>
<td></td>
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<td>120</td>
<td>117.40</td>
<td>93.84</td>
<td>80.25</td>
<td></td>
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<tr>
<td>14</td>
<td>130</td>
<td>125.10</td>
<td>101.16</td>
<td>86.43</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>140</td>
<td>132.80</td>
<td>108.48</td>
<td>92.62</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>150</td>
<td>140.50</td>
<td>115.80</td>
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<td>17</td>
<td>160</td>
<td>148.20</td>
<td>123.12</td>
<td>104.99</td>
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<tr>
<td>18</td>
<td>170</td>
<td>155.90</td>
<td>130.44</td>
<td>111.18</td>
<td></td>
</tr>
</tbody>
</table>
4.2 Pipe Decision Experiment

4.2.1 Statistical Model for Response Rate

GEE analysis with all within subject factors included in the model showed the following main effects and two-way interactions to have statistically significant effects on correctness of responses:

<table>
<thead>
<tr>
<th>Source</th>
<th>Wald Chi-Square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>24.196</td>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>Block</td>
<td>26.354</td>
<td>4</td>
<td>0.000</td>
</tr>
<tr>
<td>Location</td>
<td>80.259</td>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>Reference</td>
<td>3.802</td>
<td>2</td>
<td>0.149</td>
</tr>
<tr>
<td>refHand</td>
<td>0.035</td>
<td>1</td>
<td>0.852</td>
</tr>
<tr>
<td>Difference</td>
<td>44.281</td>
<td>3</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * Location</td>
<td>7.992</td>
<td>8</td>
<td>0.434</td>
</tr>
<tr>
<td>Block * Reference</td>
<td>40.644</td>
<td>8</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * refHand</td>
<td>2.992</td>
<td>4</td>
<td>0.559</td>
</tr>
<tr>
<td>Block * Difference</td>
<td>166.199</td>
<td>8</td>
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<tr>
<td>Location * Reference</td>
<td>4.881</td>
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<td>Location * refHand</td>
<td>5.839</td>
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<td>Location * Difference</td>
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<td>Reference * refHand</td>
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<td>0.874</td>
</tr>
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<td>Reference * Difference</td>
<td>26.494</td>
<td>2</td>
<td>0.000</td>
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<tr>
<td>refHand * Difference</td>
<td>3.455</td>
<td>3</td>
<td>0.327</td>
</tr>
</tbody>
</table>

Table 4: Derived scalar values for the temperature range in the Wrench gripping experiment

<table>
<thead>
<tr>
<th>Signal No.</th>
<th>Target Ratio</th>
<th>AM Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Finger pad</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>57.73</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>74.09</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>90.45</td>
</tr>
<tr>
<td>4</td>
<td>3.25</td>
<td>106.81</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>123.18</td>
</tr>
</tbody>
</table>
Main effects of Block, Location and Difference were significant (p < 0.0005). Interaction effects are normally only considered significant if both main effects and the interaction itself are significant. This corresponds to: Block*Difference and Location*Difference.

To construct an accurate model, the analysis was rerun again, only including the significant terms:

**Table 6: More accurate GEE analysis of Response Rate**

<table>
<thead>
<tr>
<th>Source</th>
<th>Wald Chi-Square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>27.943</td>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>Block</td>
<td>11.758</td>
<td>4</td>
<td>0.019</td>
</tr>
<tr>
<td>Location</td>
<td>63.593</td>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>Difference</td>
<td>104.269</td>
<td>4</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * Difference</td>
<td>8.31192E+14</td>
<td>9</td>
<td>0.000</td>
</tr>
<tr>
<td>Location * Difference</td>
<td>53233.798</td>
<td>8</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The marginal means for the significant main effects for the final model are shown below. The marginal means are not shown for interaction terms as no easily discernible trend occurred.

**4.2.2 Estimated Marginal Means: Location**

Pairwise comparison of means, adjusted for multiple comparisons, show only a significant difference between the finger pad and bicep locations (p < 0.0005). Although not statistically significant, there does seem to be a trend of decreasing correctness of the response for increasing distance from the finger pad.

**Table 7: Estimated Marginal Mean Response rate for Location**

<table>
<thead>
<tr>
<th>Location</th>
<th>Response Correctness</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger pad</td>
<td>0.71</td>
<td>0.037</td>
</tr>
<tr>
<td>Forearm</td>
<td>0.67</td>
<td>0.038</td>
</tr>
<tr>
<td>Bicep</td>
<td>0.6</td>
<td>0.029</td>
</tr>
</tbody>
</table>
4.2.3 Estimated Marginal Means: Signal Difference

Pairwise comparison of means, adjusted for multiple comparisons, show a significant difference between all pairwise comparisons, with all p-values < 0.0005 except for the -3 compared to “Too Hot!” which had a p-value = 0.004 and 3 compared to 5 which had a p-value = 0.046. Note that the “Too Hot!” signal consisted of no modulation of the 250 Hz sine wave. In addition, the “Proceed” signals of +/- 30 degrees generally had a higher correct response rate than “Do Not Proceed” signals of +/- 50 degrees.
Table 8: Mean response rates for signal differences.

<table>
<thead>
<tr>
<th>Signal Difference</th>
<th>Mean Response Rate</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too Hot!</td>
<td>0.94</td>
<td>0.025</td>
</tr>
<tr>
<td>-50 degrees</td>
<td>0.23</td>
<td>0.035</td>
</tr>
<tr>
<td>-30 degrees</td>
<td>0.82</td>
<td>0.041</td>
</tr>
<tr>
<td>30 degrees</td>
<td>0.63</td>
<td>0.055</td>
</tr>
<tr>
<td>50 degrees</td>
<td>0.44</td>
<td>0.051</td>
</tr>
</tbody>
</table>

4.2.4 Estimated Marginal Means: Block
Pairwise comparison of means, adjusted for multiple comparisons, shows a significant difference ($P < 0.037$) between Block 1 (68% hit rate) and Block 5 (63% hit rate).
Table 9: Mean response rates per successive testing block.

<table>
<thead>
<tr>
<th>Block</th>
<th>Response Rate</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.68</td>
<td>0.031</td>
</tr>
<tr>
<td>2</td>
<td>0.68</td>
<td>0.028</td>
</tr>
<tr>
<td>3</td>
<td>0.63</td>
<td>0.042</td>
</tr>
<tr>
<td>4</td>
<td>0.66</td>
<td>0.033</td>
</tr>
<tr>
<td>5</td>
<td>0.63</td>
<td>0.045</td>
</tr>
</tbody>
</table>

4.2.5 Statistical Model for Response Time

GEE analysis using a Poisson log linear distribution showed the following main effects and two-way interactions to have statistically significant effects on response time:

Table 10: First attempt at GEE analysis for response time

<table>
<thead>
<tr>
<th>Source</th>
<th>Wald Chi-Square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>10353.313</td>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>Block</td>
<td>6.591</td>
<td>4</td>
<td>0.159</td>
</tr>
<tr>
<td>Location</td>
<td>2.803</td>
<td>2</td>
<td>0.246</td>
</tr>
<tr>
<td>Reference</td>
<td>5.864</td>
<td>2</td>
<td>0.053</td>
</tr>
<tr>
<td>refHand</td>
<td>0.057</td>
<td>1</td>
<td>0.811</td>
</tr>
<tr>
<td>Difference</td>
<td>26.451</td>
<td>3</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * Location</td>
<td>96.791</td>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * Reference</td>
<td>35.996</td>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * refHand</td>
<td>1.988</td>
<td>4</td>
<td>0.738</td>
</tr>
<tr>
<td>Block * Difference</td>
<td>36.346</td>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>Location * Reference</td>
<td>9.529</td>
<td>4</td>
<td>0.049</td>
</tr>
<tr>
<td>Location * refHand</td>
<td>4.109</td>
<td>2</td>
<td>0.128</td>
</tr>
<tr>
<td>Location * Difference</td>
<td>72.044</td>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>Reference * refHand</td>
<td>6.837</td>
<td>2</td>
<td>0.033</td>
</tr>
<tr>
<td>Reference * Difference</td>
<td>2.073</td>
<td>2</td>
<td>0.355</td>
</tr>
<tr>
<td>refHand * Difference</td>
<td>0.876</td>
<td>3</td>
<td>0.831</td>
</tr>
</tbody>
</table>

Only the main effect of Signal Difference was significant (p < 0.0005). Interaction effects are normally only considered significant if both main effects and the interaction itself are significant. Therefore, none of the interactions effects were included in the final model. To construct an accurate model, the analysis was rerun again, only including the significant term Signal Difference:
Table 11: Second attempt at GEE analysis of response time w/ only 1 significant main effect

<table>
<thead>
<tr>
<th>Source</th>
<th>Wald Chi-Square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>9206.736</td>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>Difference</td>
<td>33.938</td>
<td>4</td>
<td>0.000</td>
</tr>
</tbody>
</table>

4.2.6 Estimated Marginal Means: Signal Difference

The “Too Hot” signal had the quickest response time and was significantly different than the response time that had temperature differences of -50 (p = 0.017), +50 (p = 0.028) and +30 (p = 0.014) degrees. The response for the +50-degree temperature difference was significantly different or close to significantly different in response time to all (+30, p = 0.055, -30, p=0.009) but the -50-degree temperature. The response for the +30-degree temperature difference was also significant different than for -30 (p = 0.001). The response time for -50 degrees compared to -30 degrees was close to significance (p = 0.52). The only clear trends are that: a) the response time for the “Too Hot” signal is different than for most other signals; b) considering the remainder comparisons, the +50-degree temperature difference (Do Not Proceed) is different than the +30-degree signals (Proceed).

Table 12: Mean Response Times for Signal Differences

<table>
<thead>
<tr>
<th>Difference</th>
<th>Response Time</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too hot!</td>
<td>1649.0859</td>
<td>130.87927</td>
</tr>
<tr>
<td>-50</td>
<td>2160.9886</td>
<td>199.24916</td>
</tr>
<tr>
<td>-30</td>
<td>2041.8783</td>
<td>193.01676</td>
</tr>
<tr>
<td>30</td>
<td>2285.8336</td>
<td>224.36067</td>
</tr>
<tr>
<td>50</td>
<td>2210.3665</td>
<td>230.91975</td>
</tr>
</tbody>
</table>
4.3 Wrench Gripping Experiment

4.3.1 Statistical Model: Response Time and Time Constant

GEE analysis using a Poisson loglinear distribution found the following the only factor to have a statistically significant effect on the steady state time constant was Block (P < 0.0005) and interactions with Block (Block*Location and Block*TargetSteadyStateRatio). However, the latter should not be included in any final model as the main effect of Location was not significant. As Block is not a particularly interesting parameter, the results from rerunning the final analysis are not included here. There was a significant difference between Block 6 and Blocks 1 and 2 on reaction time, but no real trend was discernible.

Although we normally would not consider the Location term further as it was not significant, as it is the parameter of interest, we decided to look at the mean values for each of the locations:

![Mean Reaction Time (ms) Graph](image-url)

**Figure 10: Graph of Signal Difference Response Time**
Table 13: Mean Time Constants and Reaction times for each location

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean Time Constant (ms)</th>
<th>Std. Error</th>
<th>Mean Reaction Time (ms)</th>
<th>Std. Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger pad</td>
<td>713.34</td>
<td>70.963</td>
<td>868.2</td>
<td>130.789</td>
</tr>
<tr>
<td>Forearm</td>
<td>835.4</td>
<td>113.906</td>
<td>989.38</td>
<td>125.4</td>
</tr>
<tr>
<td>Bicep</td>
<td>745.59</td>
<td>64.17</td>
<td>820</td>
<td>104.429</td>
</tr>
</tbody>
</table>

Both the time constant and the response time showed similar trends. However, none of the pairwise comparisons were statistically significant.

4.3.2 Statistical Model for Steady State Error

For the steady state error, we were expecting a Normal distribution. A direct plot of the data showed that it significantly deviated from a Normal Distribution and included an outlier.
greatly distant from the rest of the data. The outlier was removed and a square root transform was used to obtain a more Normal distribution.

Table 14: Histogram of steady state error before (left) and after (right) sqrt transform.

GEE analysis with all within subject factors included in the model showed the following main effects and two-way interactions to have statistically significant effects on correctness of responses:

Table 15: First attempted GEE Analysis for steady state error

<table>
<thead>
<tr>
<th>Source</th>
<th>Wald Chi-Square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.004</td>
<td>1</td>
<td>0.948</td>
</tr>
<tr>
<td>Block</td>
<td>42.258</td>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>Location</td>
<td>0.11</td>
<td>2</td>
<td>0.946</td>
</tr>
<tr>
<td>TargetSteadyStateRatio</td>
<td>191.207</td>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * Location</td>
<td>201.15</td>
<td>6</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * TargetSteadyStateRatio</td>
<td>3.87509E+13</td>
<td>7</td>
<td>0.000</td>
</tr>
<tr>
<td>Location * TargetSteadyStateRatio</td>
<td>392.375</td>
<td>4</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Main effects of Block and the Targeted Steady State Ratio were significant ( < 0.0005). Interaction effects are normally only considered significant if both main effects and the interaction itself are significant. This corresponds to: Block*Targeted Steady State Ratio only.
Although we normally would not consider the Location term further as it was not significant, as it is the parameter of interest, we decided to look at the mean values for each of the locations:

**Table 16: Mean sqrt steady state error, mean steady state error at each location**

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean Sqrt SSE</th>
<th>Mean SEE</th>
<th>Std. Error on Sqrt SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger pad</td>
<td>0.8954</td>
<td>0.8017</td>
<td>0.0587</td>
</tr>
<tr>
<td>Forearm</td>
<td>0.9089</td>
<td>0.8261</td>
<td>0.02532</td>
</tr>
<tr>
<td>Bicep</td>
<td>0.8596</td>
<td>0.7389</td>
<td>0.02881</td>
</tr>
</tbody>
</table>

![Mean Steady State Error](image)

**Figure 12: Graph of Feedback Location Mean Steady State Error**

Only the difference between location 3 and location 1 was significant. However, to construct an accurate model, the analysis was rerun again, only including the significant terms:
The marginal means for the significant main effects for the final model are shown below. The marginal means are not shown for interaction term as no easily discernible trend occurred.

### 4.3.3 Estimated Marginal Means: Target Steady State Ratio

Pairwise comparison of the means found that the steady state error was significantly greater for the target ratio of 4, which was significantly different than the other target ratios of 1 and 2.5.

<table>
<thead>
<tr>
<th>Source</th>
<th>Wald Chi-Square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>994.111</td>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>Block</td>
<td>12.884</td>
<td>5</td>
<td>0.024</td>
</tr>
<tr>
<td>TargetSteadyStateRatio</td>
<td>25.872</td>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>Block * TargetSteadyStateRatio</td>
<td>35.392</td>
<td>6</td>
<td>0.000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TargetSteadyStateRatio</th>
<th>Mean Sqrt SEE</th>
<th>Mean SSE</th>
<th>Std. Error on Sqrt SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7666</td>
<td>0.5877</td>
<td>0.07758</td>
</tr>
<tr>
<td>2.5</td>
<td>0.7522</td>
<td>0.5659</td>
<td>0.06753</td>
</tr>
<tr>
<td>4</td>
<td>1.145</td>
<td>1.311</td>
<td>0.07673</td>
</tr>
</tbody>
</table>
4.3.4 Estimated Marginal Means: Block

From the statistical analysis of the pairwise comparisons, no trend was observed beyond that there seemed to be somewhat of a trend to larger errors in later blocks.

Table 19: Mean steady state errors for each successive testing block

<table>
<thead>
<tr>
<th>Block</th>
<th>Mean Sq rt SSE</th>
<th>Mean SSE</th>
<th>Std. Error of Sq rt SSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8575</td>
<td>0.7353</td>
<td>0.04747</td>
</tr>
<tr>
<td>2</td>
<td>0.8578</td>
<td>0.7358</td>
<td>0.03555</td>
</tr>
<tr>
<td>3</td>
<td>0.8531</td>
<td>0.7278</td>
<td>0.05035</td>
</tr>
<tr>
<td>4</td>
<td>0.9182</td>
<td>0.8431</td>
<td>0.03053</td>
</tr>
<tr>
<td>5</td>
<td>0.8823</td>
<td>0.7785</td>
<td>0.01775</td>
</tr>
<tr>
<td>6</td>
<td>0.9588</td>
<td>0.9193</td>
<td>0.03361</td>
</tr>
</tbody>
</table>
4.3.5 Statistical Model for Rate of Force Upgrade

GEE analysis with all within subject factors included in the model showed the following main effects and two-way interactions to have statistically significant effects on rate of force (initial slope). This data was also transformed by a sqrt function to make it more normal.

<table>
<thead>
<tr>
<th>Source</th>
<th>Wald Chi-Square</th>
<th>df</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>240.036</td>
<td>1</td>
<td>0.000</td>
</tr>
<tr>
<td>Block</td>
<td>36.131</td>
<td>5</td>
<td>0.000</td>
</tr>
<tr>
<td>TargetSteadyStateRatio</td>
<td>9.47</td>
<td>2</td>
<td>0.009</td>
</tr>
<tr>
<td>Block * TargetSteadyStateRatio</td>
<td>5.976</td>
<td>6</td>
<td>0.426</td>
</tr>
</tbody>
</table>

Table 20: GEE analysis of the main effects on grip rate

4.5.6 Estimated Marginal Means: Grip Rate

Pairwise comparison of means found Target Steady Ratio of 1 was significantly smaller from the Target Ratios of 2.5 and 4.

<table>
<thead>
<tr>
<th>Target Steady State Ratio</th>
<th>Mean Sqrt Grip Rate</th>
<th>Mean Grip Rate</th>
<th>Std. Err</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.9367</td>
<td>0.877</td>
<td>0.09325</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0839</td>
<td>1.17</td>
<td>0.10014</td>
</tr>
<tr>
<td>4</td>
<td>1.2064</td>
<td>1.45</td>
<td>0.05149</td>
</tr>
</tbody>
</table>

Table 21: Mean Grip Rates (initial slopes) for each target steady state ratio.

5. Discussion

5.1 Perceptual Tasks

5.1.1 30-dB Equal Sensation Level Curve for Amplitude Modulation Signals

The 30-dB equal SL curve (Figure 3) shows the finger pad exhibits a much more uniform perception of modulation frequency intensity than the other feedback sites. The forearm is notably more insensitive than the finger pad, while the bicep is the most insensitive, especially at higher frequencies. The higher sensitivity at the finger pad could be due to a higher
concentration of FA I, SA I and SA II mechanoreceptors at the finger pads. At least in the hand there is known to be a decrease in the density of these receptors as you travel down the finger and palm and this is correlated with lower sensitivity to tactile stimulation in general (Vallbo, 1984).

It is important to note that in our experiment we did not apply a specific preload to the tactor against the skin. Instead, we chose to secure the feedback in wearable forms using the plastic rings for the finger pad and nylon sleeves for the forearm and bicep. Slight variations may arise from the differences in preload because the resulting skin indentations necessarily modulate the mechanoreceptor response.

5.1.2 Roughness Perception of Amplitude Modulated Signals

In previous work, Hoggan & Brewster showed a 250 Hz sine wave to be smooth, the same sine wave modulated by a 50 Hz carrier to be rough, and a 30 Hz carrier to be very rough. Our experiment added more points to more completely characterize the response by including the unmodulated sine wave and the following carrier frequencies: 6, 12, 24, 48, 96, 124 Hz. The form of the response was an inverted u-shape (Figure 5). At all locations, pure sinusoids (no modulation) felt the smoothest. On the finger pad, perceived roughness increased from approximately 6 Hz to 24 Hz and then declined linearly in roughness from 24 Hz to 124 Hz. For the forearm and bicep, perceived roughness was highest at 6 Hz and declined in similar fashion to 124 Hz. This trend is consistent with and expands on previous data (Hoggan and Brewster). We also considered roughness as a scalar dimension (0-100) rather than an ordinal one (rougher/smooth).
The linear region chosen for scalar mapping of each location had to start at their respective roughest points, such that one perceived value was not mapped to multiple frequencies. A generalized equation can be written as:

\[
AM \text{ Frequency of Perceived Roughness} = \text{RME intercept} + \text{slope} \times \text{scalar value}
\]

The roughness magnitude estimation was based only on subjective rankings. If the AM signals were compared to physical representations of roughness, such as gratings with distinct spatial periods moved across each feedback location at a fixed speed which already exists in a scalar dimension, it could have resembled a more accurate translation of roughness into vibrotactile stimulation.

### 5.2 Pipe Decisions Task

The effect of location on the response rate of the temperature sensing task was significant and performance decreased as the site of feedback was placed more proximal. The correct response rate to feedback at the finger pad was 71% which decreased to 67% at the forearm and again to 60% at the bicep. The accuracy at which the task was performed was significantly worse at the bicep compared to the finger pad. This may be due to the increased sensitivity due to the density of mechanoreceptors in the finger pad. The original hypothesis predicts this outcome. There was no difference in reaction time between locations, possibly because after the 1 second signal played, the sensation would quickly leave the subjects sensory memory which placed a limit on how long they could take to decide.

The signal differences varied significantly from one another in performance (Table 8). The “Too Hot” signal had the highest rate of correct responses (94%). This signal was the only
unmodulated sinusoid and was above the 30-dB line. It was designed to match the peak performance of the C3 tactor to produce the most power vibrations to act as an alarm when the user was in a dangerous situation. Thus, the reaction time to the “Too Hot” signal had the best performance with a time of 1.6 seconds.

Inspecting response rate variance between positive and negative differences of the same amount, shows -30 degrees from the reference performed better than +30 degrees from the reference and +50 degrees from the reference performed better than -50 degrees from the reference (Table 12). A greater percentage of the negative differences come from higher in the frequency range, because there can be no positive difference for the reference temperature of 160 (Table 3). The frequencies corresponding to temperatures 140-170 are above 124 Hz, which had to be extrapolated from the RME as it was not tested. If the linear decrease in roughness stopped in this high frequency range and instead was a flat response, it could explain the higher success rate of -30-degrees and higher fail rate of -50-degrees differences.

The time it took to react to all signal differences was between 2.0 and 2.2 seconds (Table 12). There was no significant effect of location on reaction time either. This suggests subjects took the maximum amount of time sensory memory allowed to make a decision, so the signals were either insufficiently long or the informational load was too high.

Simultaneously receiving signals on either side of the body may have been mentally and attentionally demanding. If the experiment was designed to include a condition where subjects felt the signal serially and unilaterally, the effect could have been investigated.
5.3 Wrench Gripping Task

The fastest reaction time was measured while the feedback was placed on the bicep (820 ms) followed by the finger pad (868.2 ms) and the forearm (989.38 ms). Additionally, when feedback was placed on the bicep, the mean steady state error was the lowest (0.74) compared to the forearm (0.83) and finger pad (0.80).

The overall performance of the bicep over the finger pad and the rejection of our original hypothesis may be attributed to the interference vibrotactile stimulation may have on the proprioceptive sense of joint angle at the finger. Vibrotactile stimulation has been shown to create an illusory sense of joint movement at the finger (Bark, et. Al, 2008). When feedback is applied on the bicep it is also closer to the central nervous system which could account for shorter reaction times. Previous studies have shown that nonsignificant differences in reaction time to touch stimuli have been observed and attributed to distance from the CNS. Muscle and joint afferent units may also have important roles in tactile sensibility (Vallbo, 1984). So, muscles that are potentially activated during the task nearby feedback locations at the finger and forearm may interfere with proper perception of the signal.

Johannson and Westling found that the settling time after picking up an object in a precision pinch grip was about the same (1.0 second) regardless of the surface roughness - silk (smooth), suede (rougher), or sandpaper (very rough). The frictional surface properties were determined to have entered the central nervous system during the 80 ms preload phase.

In comparison, the settling times at each location in our experiment were 2.8 times longer at the finger pad, 3.3 times longer at the forearm and 2.9 times longer at the bicep. Part of this large discrepancy is due to the long reaction times when compared to the short preload
times where frictional information is quickly sensed and processed over 10 times faster. This is maybe the effect of indirect feedback requiring conscious effort rather than the direct intuitive tactile feedback of the skin.

A limitation of our design which may have affected our results was not including varied weights (load force) to compare the response of vibrotactile feedback to the natural response. The two main factors of balancing grip to load force are the weight of the object and the frictional surface properties of the object. We could have more completely compared results to Johannson and Westling’s research to fully characterize the effect representing the load ratio as vibrotactile feedback has on the control of precision grip.

6. Conclusion
In this study we constructed a 30-dB equal sensation level curve for amplitude modulated frequencies at three locations along the upper extremity. Those 30 dB SL signals were placed in a scalar dimension of roughness by subjective magnitude estimation. We mapped sensory information onto the scalar dimension such as temperature and frictional surface properties and applied vibrotactile feedback to manual tasks to investigate the effect different locations would have on performance.

Although there have been some studies (e.g., Jones and Sarter, 2008, for a review) comparing perceptual performance of body sites, this has not been extended to actual functional tasks. Response time has also not been considered. Furthermore, although the use of AM signals has been investigated in the past, only a few different, highly disparate parameter
values have been examined. There has also been no previous attempt to disambiguate perceived magnitude and AM frequency, which have been shown to interact with changes in physical amplitude and body site.

Our experiments have found task performance increase when the feedback location and site of action are co-located for sensory tasks and decrease for manipulatory tasks. Sensitivity of the hands and fingers to vibrations lend to the success of sensory feedback located on the finger pads. Muscle activation may interfere with the perception of vibratory feedback or vice versa, so more distal feedback locations are advantageous.

In terms of applications: While applying vibrotactile feedback to prosthetic systems may not be a new idea, designing the feedback as a function of perceived roughness which mimics the frictional aspect of objects being grasped proved to be advantageous with respect to the rate at which grip force was applied. Our original hypothesis of performance decreasing as feedback was moved up the arm proved to be correct only for response rate for the temperature sensing task. This research opens the possibility to replacing one impaired cutaneous sense (thermoreception) with a vibrotactile recreation to restore a natural safety reflex to dangerous heat conditions.
References


Appendix: Diagrams

Figure 14: Tactor Driving Circuit: Vcc +/- 7 volts; R1 = 1M Ohm; R2 = 30 Ohm; Q1 = NPN Transistor; AC signal provided by Labview DAQ.
Figure 15: Labview Script for Generating AM Signals
Figure 16: Labview Script for Triggering Signal for Pipes Experiment.
Figure 17: Labview Script for Selecting and Playing Signals for Pipes
Figure 18: Labview Script for Triggering Signal for Wrench Experiment
Figure 19: Labview Script for Selecting and Playing Signals for Wrench