Haptic Discrimination of Object Size Using Vibratory Sensory Substitution

by

Markey Olson

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Stephen Helms Tillery, Chair Christopher Buneo Marco Santello

ARIZONA STATE UNIVERSITY

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ABSTRACT

Humans constantly rely on a complex interaction of a variety of sensory modalities in order to complete even the simplest of daily tasks. For reaching and grasping to interact with objects, the visual, tactile, and proprioceptive senses provide the majority of the information used. While vision is often relied on for many tasks, most people are able to accomplish common daily rituals without constant visual attention, instead relying mainly on tactile and proprioceptive cues. However, amputees using prosthetic arms do not have access to these cues, making tasks impossible without vision. Even tasks with vision can be incredibly difficult as prosthesis users are unable to modify grip force using touch, and thus tend to grip objects excessively hard to make sure they don't slip.

Methods such as vibratory sensory substitution have shown promise for providing prosthesis users with a sense of contact and have proved helpful in completing motor tasks. In this thesis, two experiments were conducted to determine whether vibratory cues could be useful in discriminating between sizes. In the first experiment, subjects were asked to grasp a series of hidden virtual blocks of varying sizes with vibrations on the fingertips as indication of contact and compare the size of consecutive boxes. Vibratory haptic feedback significantly increased the accuracy of size discrimination over objects with only visual indication of contact, though accuracy was not as great as for typical grasping tasks with physical blocks. In the second, subjects were asked to adjust their virtual finger position around a series of virtual boxes with vibratory feedback on the fingertips using either finger movement or EMG. It was found that EMG control allowed for significantly less accuracy in size discrimination, implying that, while proprioceptive feedback alone is not enough to determine size, direct kinesthetic information about finger position is still needed.

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CHAPTER 1

INTRODUCTION

At any given time, humans process constant visual, tactile, and proprioceptive feedback in order to determine their position in space. Visual information allows for a large number of object characteristics including color, shape, and size to be quantified before direct contact is even made. Tactile and proprioceptive feedback, on the other hand, are generated by the peripheral nervous system in response to provide feedback about the current state of the body and external objects it is in contact with. Tactile sensation arises from activation of four subsets of mechanoreceptors located within the skin that contribute to feelings of touch, pain, flutter, and vibrations (Johansson, 2009). Meissner corpuscles, Merkel disks, Pacinian corpuscles, and Ruffini endings each encode for unique touch features including light touch, deep pressure, vibration, and temperature (Johansson, 1977). In contrast, proprioception refers to body position and movement, and encodes for both quantifiable parameters such as force, position and velocity and more subjective qualities like effort (Jones, 1994). This information is transmitted through a variety of mechanoreceptors in the muscles and skeletal system: including nuclear bag fibers, nuclear chain fibers, Golgi tendon organs, and joint capsule receptors (Houk, 1967), though an increasing body of research shows that the traditionally tactile receptors in the skin also play a role in proprioception (Proske, 2012).

Visual guidance is generally necessary for accurate movements during reach. It is necessary for humans to be able to view both their hand and the object to be manipulated during the reaching motion in order to accurately pre-shape the hand for effective grasp (Lee, 2008). Even in tasks that are considered largely proprioceptive, visual feedback seems to play a large role. Helms Tillery (1991) showed that, when the arm of a subject was passively displaced while while their eyes were shut, the subject was unable to accurately indicate the new location of their hand using a pointer after the trial completion. This suggests that kinesthetic input by itself is not enough to give humans a sense of where their body relative to other objects in space.

Even when vision is available, tactile and proprioceptive feedback is needed in order to detect object density as well as twist or slippage and to appropriately modulate grip force to

prevent motion (Jenmalm, 2000). Without the mechanoreceptors in the skin providing tactile sensation, we are unable to make needed corrections in grasp even with constant visual guidance. Vision does not provide fast enough indication of slip to allow for modification of grip before major slippage occurs (Westling, 1984). It appears that visual information may be able to compensate for proprioceptive cues, at least in some instances, but it can not replace touch.

Humans are still able to complete most daily tasks, even those involving reaching, without constant visual information. It is guite common for reaches and grasps to be accomplished without visual feedback, especially when attention is divided between several tasks. Haptic feedback, that is, the tactile and kinesthetic input generated from mechanoreceptors, allows for this. There are many situations where people must focus on a visual task (e.g., watching a lecture or movie) while working on another task using kinesthetic feedback (e.g., reaching for a pencil in a backpack or grabbing a remote that fell on the floor). For most people, this is not a problem, especially for common tasks that have been completed before and can be guided largely by memory. The movement is not apt to accurately grasp the object on the first try, but kinesthetic information is enough to eventually grab and identify the needed object. While visual contact is useful for the initial location and contact of an object, the final grasp position is not affected by lack of vision (Santello, 2002). Once contact is made, subjects can also use tactile and proprioceptive feedback alone to update grip force and position (Blank, 2008). The ability for humans to modify the forms of feedback used for a task based on current needs is thought to be due to a maximum-likelihood integrator, which estimates the feedback mechanism carrying the minimum amount of variance for a given task and weights each feedback mechanism accordingly. Thus, when vision is available for a given trial, it is weighted more heavily than other forms of feedback if they are less reliable, such as in reaching trials. However, when vision is occluded, these forms of feedback are given higher weight to allow for continuous information update (Ernst, 2002). While the brain does try to utilize and integrate all three modalities when possible, it is quite flexible in processing the information it is given (Desmurget, 1998). For example, vision is relied upon for many tasks, especially those involving accurate reaching movements, but people can typically perform a variety of common daily tasks without constant

visual attention, instead relying on tactile and proprioceptive cues. With proprioceptive and tactile information both available, subjects are able to identify the configuration of their joints and relative position in space with a high degree of feedback (Han, 2016; Hillier, 2015).

The simplest of tasks requires the complex interworking of these sensory pathways to integrate information about object size, shape, weight, density, and texture and to use this information to appropriately interact with objects. Visual information is used to determine object characteristics even before movement begins, and these properties and the intended object use are used to develop both feedback and feed-forward loops to determine proper each and grasp patterns (Desmurget, 1998). During reach, vision and proprioception are used together, with proprioception being weighted more strongly, to determine hand position in space relative to the object and to continually recalibrate needed trajectory and hand joint angles before contact is made (Binsted, 2001). Tactile feedback acts to correct error and maintain appropriate grip force once the object is reached (Coats, 2008).

Tactile and proprioceptive feedback are not readily available for prosthesis users, however. Even the most technologically advanced hands currently available, while containing an impressive number of degrees of freedom and the ability for life-like range of motion, are not able to present detailed sensation to the user. Vibrations traveling from the prosthesis to the residual stump during contact can provide rudimentary information, but it is not extremely helpful for actually determining object and grip characteristics. Without haptic representation of their current hand position relative to the object they hope to interact with, prosthesis users require constant visual guidance to accurately complete tasks. A survey of 2,477 prosthesis users found that the ability to complete tasks with less visual attention was one of the most pressing demands of users, and a major factor contributing to the incredibly high rate of disuse as reported by patients and physicians. The ability to better grasp objects was also found to be incredibly salient to users (Atkins, 1996). Because of the importance of somatosensory feedback in the appropriate scaling of grip force (Johansson, 1991), prosthesis users often adopt an excessive grip force when grasping objects in order to ensure that the object does not slip. This overestimation of needed

grip force can result in muscle fatigue in the residual arm as well as object deformation and damage.

It can be difficult to distinguish the exact roles of the haptic senses. Both tactile sensation and proprioception are generally intertwined and must be used in conjunction in order to accurately measure object characteristics in relation to the body. Subjects cannot perform size discrimination tasks using tactile information in isolation. Proprioception alone is useful for size discrimination tasks, but it provides only a very rough estimate, with subjects greatly underestimating the size of the objects, likely because they squeezed the deformable objects much harder in the absence of tactile sensation (Berryman, 2006). Tactile feedback has also been found to improve accuracy of reported arm location, showing that tactile and proprioceptive information may be intertwined even for tasks traditionally considered proprioceptive (Rincon-Gonzalez, 2011). Another study showed that humans are better able to estimate the position of their hand over a workspace if they are allowed to touch the position on the workspace that their hand was passively moved to before it was returned to resting position (Rincon-Gonzalez, 2012). The degradation in ability to perceive relative joint position without tactile information varies largely based on the joint being studied (Clark, 1986). Tactile illusions such as the cutaneous rabbit effect, which is dependent on the posture of the fingers, further complicates our understanding of proprioceptive vs. tactile feedback (Rincon-Gonzalez, 2011; Warren, 2011).

In order to understand the role that sensory substitution, a method of transforming information traditionally processed by one sensory modality into another, could play in introducing these senses to prosthetic designs, the typical interaction of these senses in grasp must be understood. While both proprioception and touch utilize specialized forms of mechanoreceptors which are processed in neighboring areas of the somatosensory cortex, proprioception uses receptors mainly within the muscles and joints to form a representation of hand position and finger aperture throughout reach and grasp (Berryman, 2006). The tactile sense determines the form, texture, location, intensity, and velocity of an external object during contact using receptors within the skin (Mountcastle, 2005). Haptic feedback, the transformation of tactile information into vibratory cues, has also been found to significantly increase the effectiveness of teleoperators at

assembly tasks when compared to traditional video monitoring (Petzold, 2004). Humans are also able to integrate haptic feedback about discrete events when accomplishing a simple lifting task using a robotic arm (Cipriani, 2014).

Vibratory sensory substitution has shown some ability to incorporate meaningful tactile information into a prosthetic environment in previous research, though it can not replace proprioceptive cues. The use of vibratory haptic feedback has been shown to improve the accuracy of subjects trying to complete a grasping task with a scroll wheel when provided upon contact with the virtual objects (Witteveen, 2012). Incorporating tactile and proprioceptive information into prosthetic devices could allow for better control of grip forces for object manipulation both with and without vision and improve user satisfaction and the rate of continued usage. Sensory substitution provides one potential avenue to accomplish this goal.

When the type of feedback provided is held constant (proprioception either with or without tactile cues), grip force and finger aperture do not play a role in the accuracy of size discrimination (Berryman, 2006). If the subject is able to maintain contact with the object with the thumb and at last one finger, regardless of which digit it is, accuracy will remain relatively stable (Santello, 1997). This ability is due to the coordination of the degrees of freedom within the palm and fingers. Humans tend to optimize neural patterns of joint activation in order to reduce the total number of active degrees of freedom during specific movements, allowing fewer joints to move in the path to a desired location (Kang, 2004; Domkin, 2005). By doing so, the thumb and fingers are able to more easily scale to object size, and the simplified computation of joint angles allows for easier comparison of joint aperture even between fingers (Santello, 1997).

In order to test whether vibratory haptic feedback could be used to replace tactile cues for size discrimination in the absence of visual attention, I asked subjects to grasp a series of virtual blocks varying in size by between 2 to 12 mm. Vibratory feedback was given upon contact with the objects. Subjects were asked to compare the sizes of each concurrent pair of boxes. The accuracy of those responses was then compared to that of two other tasks being completed concurrently by other members of my lab. The first task asked subjects to compare the sizes of a series of physical blocks while the second test presented a similar virtual reality environment to

my own but expressed contact with visual indicators instead of haptic ones. It was found that, while still not as accurate as traditional tactile feedback using physical boxes, vibratory sensory substitution presented a distinct advantage over visual indicators of contact, showing some promise at being used in prostheses for size discrimination in addition to the more conventional tasks described above.

While vibratory feedback was helpful for size discrimination for tasks involving finger movement, prosthesis users are required to grasp objects without the use of proprioception through their fingers. Thus, it became important to test whether the initial results would extend in situations where "finger" movement is not directly related to change in proprioceptive sensation. To do so, two new virtual reality trials were run. In the first, finger aperture was controlled by the movement of the fingers. In the second, EMG sensors were used to monitor flexion and extension of the elbow, which changed the aperture. EMG made for a sensible way to create decoupled proprioceptive feedback as it is currently used to control a variety of prostheses.

CHAPTER 2

EFFECTIVENESS OF VIBRATORY HAPTIC FEEDBACK FOR SIZE DISCRIMINATION METHODS

A total of sixteen subjects between the ages of 19 and 49 with no known neurological conditions were asked to complete a virtual reality task in which they grasped a series of objects and compared each consecutive block to the one immediately before it. All procedures were reviewed and approved by Arizona State University's Institutional Review Board. Each subject completed a total of 110 trials, with the first ten being training trials. With the exception of the training trials, in which the virtual object and the finger locations were visible, an opaque shield surrounded the blocks, rendering the area around them invisible (Figure 1a). This shield was visible during the training trials, but it was set to be transparent to allow for clear sight of the block and fingers in the space. Blocks were generated in a randomized sequence and varied in size between 44 and 56 mm (in two mm increments), though the sequence was modified to ensure that the same size never occurred in two consecutive trials.



Figure 1: Screenshots of the haptic game while in play. The first picture (Figure 1a) shows the screen while a grasping trial is being completed. The shield in the center of the screen hides a rectangular solid with width of between 44 and 56 mm. The second (Figure 1b) is an image from the subject response phase of the trial, in which subjects are asked to move both fingers to one of the response boxes to indicate whether the box just grasped was smaller or larger than the one before it.

Subjects controlled virtual fingers using their own finger position as measured by two PhaseSpace markers placed in the tip of the thumb and index finger. In order to initially calibrate position, subjects were asked to place their fingers together at a comfortable location on the workspace and the virtual finger positions were set to appear together on the center of the screen. Resultant movements from this position than caused changes to the virtual finger position in the corresponding direction. Contact with the edges of the virtual object was indicated by vibratory haptic feedback applied through vibrators placed on the corresponding fingertip (Figure 2). The vibrators were connected to an Arduino Micro microcontroller that was placed on an adjustable band on the wrist and received commands from the virtual environment. Once subjects were able to maintain contact with the object with both fingers simultaneously for 200 ms, two boxes appeared on either side of the shielded area (Figure 1b). These cubes were used for size comparison response, and subjects were required to move both fingers into one of these boxes (which were labeled smaller or larger) in order to give their answer and proceed to the next trial. Block sizes and subsequent subject responses were recorded for further data analysis in Matlab.



Figure 2: The physical setup for the game. PhaseSpace markers were placed on the subject's thumb and index fingers and held in place by medical tape. Vibration motors in an adjustable Velcro sleeve were then placed over the medical tape.

The accuracy of subjects' responses for this experiment was compared to that of subjects completing two other experiments conducted concurrently by two other members of the SMoRG lab. Both tasks asked subjects to make a size comparison between consecutive blocks of randomized sizes between 44 and 56 mm. However, in the first, subjects were asked to grasp a series of physical blocks that were hidden behind an opaque screen with a small cutout for the hand. Subjects gave response verbally and their responses were recorded manually, along with object size. The second task had much the same virtual setup as my own, but vibrators were not attached to the subject's fingertips. Instead, cues about contact were provided using visual indicators outside of the shielded region on the side of the finger making contact. Response was recorded the same way as in the haptic trials.

A total of ten subjects completed the physical block task and fifteen subjects participated in the virtual task without haptic feedback. Three subjects completed all three tasks and two participated in both virtual tasks, while the rest of the subjects completed only one task.

RESULTS

Data from all subjects were first plotted based on trial type: physical blocks (Figure 3a), virtual blocks without vibratory sensory substitution (Figure 3b), and virtual blocks with vibratory sensory substitution (Figure 3c). The plots organized the percentage of trials in which subjects responded that the block was larger for each possible difference in object size between consecutive trials (2 to 12 mm). Exclusion criteria were applied during this step. Subjects that incorrectly answered more than 50% of the trials involving the largest size difference (+/- 12 mm) were considered to be insufficiently engaged with the task, and their data were excluded from further analysis. Based on this criteria, one subject was excluded from the virtual task with haptic feedback and four subjects were excluded from the haptic task.



Figure 3: The percentage with which each subject replied that the object was larger than the one preceding it for physical trials (Figure 3a), virtual trials without haptic feedback (Figure 3b), and virtual trials with haptic feedback (Figure 3c). Responses were grouped by the actual change in size between consecutive trials. This figure is from a paper currently being published by members of the SMoRG lab.

Subject data were then aggregated, and the mean percentage of subject response being larger for each size difference was plotted for each of the three tasks (Figure 4). It was expected that a psychometric curve would be observed for each task, with subject responses achieving a high level of accuracy for large size differences between trials but being less accurate when size differences were very small. As shown by the black line in Figure 4, this trend was clear for physical blocks. Subjects almost never responded that the object was larger than the one immediately preceding it when it was much smaller, but almost always did so when it was much larger. Perfect discrimination was reached for the largest size differences (+12 mm and -12 mm) for this task, and subjects responded with 90% accuracy for objects different in size by at least 6 mm. Neither virtual task was able to reach this level of accuracy. This trend is not so clearly seen for the virtual trials. While accuracy does increase based on the magnitude of the size difference between trials, subjects never achieve full accuracy and the response larger profile more closely resembles a linear function that the expected S-shaped psychometric curve. Because of this, a linear regression was performed on the data in order to compare performance between tasks (Figure 5).



Figure 4: The mean percentage of subject response being larger for each size comparison. The error bars represent standard error of the mean.



Figure 5: Linear fits of the data based on trial type.

The data from these linear fits were then used to determine the bias and sensitivity of each trial type (Figure 6). Bias was calculated as the deviation from zero size difference in which subjects' mean response became larger more than 50% of the time. Sensitivity was measured based on the slope of the fit line. Bias was not found to be significantly affected by trial type when tested by a one-way ANOVA (Figure 7), but this was thought to be largely due to the large variance in bias between subjects for the vibratory trials without haptic feedback. There was a small but significant difference in bias between the physical trials and the virtual trials with haptic feedback (t-test with Bonferroni correction, p<0.0167). Experiment type did have a strong effect on sensitivity (one-way ANOVA, p<0.0005). All trial types were significantly different from each other (multiple comparisons test, p<0.05).



Figure 6: An example showing the bias and sensitivity of the linear fir for physical trials. Bias was determined by the size difference from zero in which the linear fit of subject response larger reached fifty percent, and the sensitivity measured the increase in subject response larger per increase in size difference in mm.



Figure 7: Boxplots of the bias and sensitivity data based on the linear fits of subjects' mean response.

Discussion

Based on the results of this experiment, proprioceptive information alone provides a very poor indication of hand position and stereognosis. Subjects experienced great difficulty in discriminating between small changes in finger aperture without tactile feedback. The nuanced feedback provided by the physical boxes was the most helpful in improving accuracy; however, even simple binary vibration signals (on or off) was able to significantly improve sensitivity to size changes.

The enhanced tactile ability of the hand enhances the proprioceptive ability and appears to play a role in proprioception not otherwise observed in the rest of the body. Tactile receptors, specifically the SAII fibers that encode for skin stretch, clearly play a role in kinesthetic sensation (Edin, 1991). Applying digital anesthesia to the skin distal to the joints of the finger produces significant deficits in the ability of subjects to make proprioceptive judgments (Clark, 1986; Day, 1981). Tactile stimulation has only been found to cause functional improvement in movements incorporating the hand (Rincon-Gonzalez, 2011; Clark, 1979). As seen in our experiment, even very rudimentary binary vibratory feedback significantly increases the accuracy of proprioception. Schemes that provide a more natural tactile sensation as well as demanding fingers stop at the edges of the object without entering could further increase task accuracy.

The relative inefficiency of proprioceptive perception within the hand could actually prove useful for the field of prosthetics. If proprioceptive sensation from muscle spindles and other mechanoreceptors within the muscles and joints of the fingers was the major force driving fine judgment of finger position, prosthetic limbs would have to find a way to accurately encode for finger position, which would be difficult due to the still ill-defined methods of proprioception within the hand. Stable sensory percepts of finger position have been generated through nerve stimulation (Dhillon, 2005), but it would take extensive research in order to isolate the nerves to be activated in order to elicit specific sensations. On the other hand, tactile sensation may be able to be provided externally, as shown by this experiment. Based on the results of this experiment, a further study was designed in order to test the effect simple binary vibratory feedback may have for prosthesis users in the absence of proprioceptive information about the hand.

The research presented in this chapter is currently in review to be published by members of the SensoriMOtor Research Group.

CHAPTER 3

METHODS

Subjects

Ten subjects between the ages of 18 and 45 with no known neurological conditions were recruited for the study. All procedures were reviewed and approved by Arizona State University's Institutional Review Board. Each subject was asked to participate in two virtual size discrimination tasks with haptic feedback. In the first, on-screen finger position was controlled by subjects' finger aperture, much like the previous experiment. In the second, subjects were asked to control finger position via flexion and extension of the elbow, as measured by EMG recording, decorrelating proprioceptive feedback from the vibratory haptic feedback supplied at the fingertips.

Correlated Proprioceptive Feedback

In the first task, subjects were asked to interact with a virtual reality environment much like that shown in Figure 1. However, there were several key differences in the control mechanisms used for the task. Instead of virtual finger position changing based on the position of the subject's fingers within the PhaseSpace workspace, only the aperture of the fingers was taken into account. The thumb marker was held at a constant position on the screen, and the blocks and the shield preventing sight were moved to accommodate this (boxes were loaded so that the thumb marker automatically made contact with the left side of the box and the shield was shifted to ensure that the object was still completely encapsulated. The right marker then moved based on the distance between the subject's fingers, as measured by the PhaseSpace markers.

The method of subject response also changed in these trials. Because the position of the thumb was held constant, there was no way for subjects to move their fingers to a location outside the shield, thus necessitating a new response scheme. The game was changed so as to allow a keyboard response of 'I' or 's' to denote whether the box just grasped was larger or smaller than the previous object. The subject provided a verbal response that was then recorded by the experimenter. A green indicator was used to denote that contact with the right edge of the box held been maintained for 200 ms and the subject was free to respond (Figure 8).



Figure 8: Screenshot of the subject response phase of the trial for the task.

The physical apparatus the subject used to interact with the system was identical to that shown in Figure 2. However, the Arduino code responsible for directing vibration was modified so that both vibrators provided stimulation when contact with the box was made by the right index finger. This prevented the vibrator on the thumb from being constantly active, but allowed for feedback to affect both digits. Subject data were recorded the same way as in previous virtual experiments.

Decorrelated Proprioceptive Feedback

For the second task, subjects were asked to use the biceps and triceps activation to control the virtual fingers on the screen. The game outlined in the task above was modified to adjust finger position based on the reading from two EMG sensors connected to an Arduino Uno microcontroller. The EMG sensors were connected to the biceps (flexion) and the lateral head of the triceps (extension) muscles (Figure 9). Before the virtual environment was loaded, the raw readings from the sensors were read into the serial monitor of the Arduino in order to determine the thresholds for muscle activity for both flexion and extension for the subject. Subjects were asked to flex their arm for ten seconds, relax for ten seconds, extend their arm for ten seconds, and relax again. This sequence was repeated three times. Based on the EMG values recorded during this time frame, the lowest value reached during the movement corresponding to activation of ach muscle group was recorded, as was the highest value reached during relaxation or

movement meant to activate the opposing muscle group. These two values were then averaged to obtain an activation threshold for each EMG sensor. These thresholds were then inputted into the Arduino code that would interface with the virtual environment. The Arduino sent data to the game so that EMG muscle activation of the extensor muscle caused the virtual finger aperture to increase while flexor activation caused aperture to decrease.



Figure 9: Pictures of the locations of the EMG sensors on the arm. The first sensor (left) was placed on the biceps in order to measure flexion EMG. The positive and negative electrodes (red) were placed on the main muscle belly and the reference (black) was placed on a bony section of the elbow. The second sensor (right) was placed on the triceps in the same fashion to measure extension EMG.

Except or the method of controlling virtual finger movement, the game was kept identical to the correlated proprioceptive feedback task. Vibrators were also kept on the fingertips the same way, though the PhaseSpace markers were removed. No other changes were made to game setup or data collection.

CHAPTER 4

RESULTS

Subjects were asked to give subjective feedback about the EMG task and the strategies they used to complete it. All subjects found that EMG control was more difficult to control than using finger aperture, even without taking the forced choice task into account. Still, subjects were able to use EMG to control movement direction and joint position (Figure 10). Muscle activation levels were sufficiently high for most subjects to allow for threshold values to be set so that they were only reached upon intentional contraction of the analogous muscle. Subjects did report that it required more effort to reach these threshold values as their arm grew fatigued towards the end of the trials, and two subjects did have isolated incidents of coactivation during the last few trials in which both thresholds were reached when they strained to try to reach the threshold for one muscle body. Subjects also reported some difficulty stopping muscle activation precisely upon feeling vibration, which caused them to have to make small movements to correct position after initial contact, but this difficulty decreased as they grew used to the control scheme.



Figure 10: The reaction of the virtual environment to EMG stimulus. Virtual finger aperture (top plot) increases when extensor EMG (red) is above threshold and decreases when flexor EMG (blue) is above threshold. In the case shown, extensor threshold was set to 190 mV and flexor threshold was set to 150 mV (as shown by the dashed lines).

Individual subject data were plotted based on trial type: virtual finger movement controlled by finger aperture (Figure 11a) and virtual finger movement controlled by EMG (Figure 11b). The plots present the rate in which subjects responded that the current trial block was larger than the one directly proceeding it, organizing responses based on the actual size difference between trials. Subject data were then averaged and the mean subject response was plotted with standard error (Figure 12). Subjects were able to achieve a high level of accuracy during the finger aperture controlled trials; indeed, these trials more closely resemble the physical trials from the first experiment than the virtual tasks. This is likely because this experiment did not require subjects to move their fingers or completely close them in order to place them in another block for response, which decreased the time between trial grasps and made direct object comparison possible with minimal movements. EMG trials did not show the same level of accuracy, however, even though the same protocol was observed. A two-way ANOVA was then run to compare the accuracy of the two groups and found that they were significantly different (p-value=5.76e-21).



Figure 11: The percentage with which each subject replied that the object was larger than the one preceding it for finger aperture (Figure 10a) and EMG (Figure 10b) controlled trials.



Figure 12: Average subject response by trial type.

While the inability to access proprioceptive information about finger position did significantly degrade the accuracy in which subjects could observe size differences between trial blocks, there was still some change in perception based on object size. Without vibratory feedback, prosthesis users would be unaware of when they contacted an object in the absence of visual guidance, and thus it would be expected that the determination of object characteristics such as size would be at chance accuracy. The average subject response was plotted in relationship to the average chance response for two possible answer choices (Figure 13) and an ANOVA was used to compare the accuracy of the subjects with chance accuracy of 50%. The two groups were found to be significantly different (p-value=3.60e-11).



Figure 13: The average rate in which subjects responded that boxes were larger than the one previously grabbed, organized by actual size difference between trials, in comparison to chance response rate.

The effect of learning and fatigue on subject accuracy for the EMG-controlled trials was also analyzed. Subjects reported a learning curve for using the EMG to adjust finger position in the first few trials, and several reported some difficulty adjusting finger position towards the end of the experiment due to the lowering of active signal thresholds once the muscles of the upper arm became fatigued. In order to test the effect of these difficulties, an ANOVA was used to compare the accuracy of the first 20 trials after training, middle 20 trials, and final 20 trials. No significant difference between the three groups was found (p-value=0.17), and multiple comparisons found no significant difference between any pair of groups. Thus, while subjects reported certain difficulties at the beginning and end of the EMG trials, they did not significantly affect the accuracy of size discrimination.

CHAPTER 5

DISCUSSION

The difference in size discrimination accuracy seen between finger aperture and EMGcontrolled experimental tasks highlights the need for research intended to be applied to the improvement of the prosthetics industry to mimic the conditions prosthesis users will be working in as closely as possible. While the results from the preliminary experiment in Chapter 2 seemed to show that even simple binary vibratory feedback carried some promise for allowing patients some level of stereognosis, significant degradation of this ability occurred when no direct proprioceptive feedback was provided about the hand. While subjects were aware of the basic control scheme of the EMG device (that is, that biceps activation caused aperture of the virtual fingers to decrease while triceps activation caused increased finger aperture), they were unable to translate the amount of muscle activation required by each muscle respectively into accurate data about object size, due of lack of accurate kinesthetic awareness. Subjects were aware of directional changes and time of movement but had no information of specific finger position. Proprioceptive information alone was not sufficient to allow for size discrimination in the first experiment, but kinesthetic information about finger position appears to still play a direct role in stereognosis.

Part of the subjects' inability to determine size differences using EMG likely arises from the back and forth motion most subjects used in order to grasp the virtual blocks. Because the flexion an extension of the elbow is generally not required to perform very fine movements that require immediate muscle deactivation, subjects experienced difficulty stopping the virtual marker at the exact moment they felt the vibration that signaled contact with the edge of the box. This resulted in the virtual finger continuing to move and leaving the edge of the box. Subjects then tried to use very small twitch-like movements to return the finger to the required position to grasp the box and end the trial, which sometimes required several movements in either direction. Because they had to move in both directions, subjects had difficulty comparing the precise amount of movement that they had accomplished in either one, making size comparison difficult. It is important to note that a prosthesis user grasping a physical object would not be able to move their hand into the object itself, which might help to prevent such back and forth motion and improve accuracy. However, it is possible that, wanting to prevent damage to the object being grasped, prosthesis users will attempt to loosen their grasp and thus begin the same cycle. Further research is needed to determine whether subjects grasping physical blocks using EMG and vibratory haptic feedback with a prosthesis or robotic hand are able to achieve higher accuracy than those grabbing virtual blocks because of the incorporated hard stop upon contact. Another interesting question posed by such research would be whether, with training, users of such a system could learn to more finely control the timing of the activation and deactivation of their biceps and triceps muscles without visual guidance.

While subjects were not able to discriminate between object sizes with the same accuracy using EMG as when allowed to actually move their fingers, they still responded better than would be expected without feedback about contact. This implies that, while not a perfect method of incorporating feedback, it would provide more knowledge of hand and finger position than that currently provided by myoelectric prostheses. Vibratory feedback provided in a different way so as to give information about finger aperture instead of contact made has demonstrated the ability to help subjects determine the placement of virtual fingers (Witteveen, 2012, p. 1517), but this feedback may not be helpful for practical life tasks, especially for those without visual guidance. Other studies have also found vibratory feedback helpful for tasks involving object manipulation without size discrimination (Rombokas, 2013, p. 2226; Stepp, 2011, p. 1061). The increased functionality of myoelectric prostheses with vibratory tactile feedback both with and without visual guidance may help to promote continued usage of prosthetic devices, even though feedback is not as robust as that given naturally.

It is possible that using another method of EMG control in which thresholds of muscle activation encode directly for finger position instead of finger movement relative to current position might also increase accuracy of size discrimination. However, such a method may be difficult to program in a way that allows for consistent graded thresholds so the user knows exactly what position he is generating with a specific motion or perceived force. Recorded values of activation for EMG tend to change based on muscle position and level of fatigue, and systems in which multiple thresholds are used are more prone to be affected by these changes than a system requiring a single threshold for each muscle group. Further study is needed to determine whether a different control scheme would allow for greater accuracy without sacrificing consistency and functionality.

Finally, for any control scheme or feedback method used, it is important to consider the perceptions of the user as well as the statistical benefits of the device. Users are less likely to use a device that they find to be difficult to operate or inconsistent, even if the functionality of the device for its intended purpose is not affected. For example, though the accuracy of size discrimination was not affected by subjects' fatigue, some subjects became frustrated with the EMG controls during the last trials because they had to flex or extend their arm with much more effort to generate the thresholds needed to move the virtual fingers. Changes in arm placement may also affect threshold activation values and lead to frustration if the user is unable to generate movement or if unintended movement of the fingers is initiated.

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APPENDIX A

IRB DOCUMENTS

Tactile and proprioceptive senses in the upper limb of humans

I am a researcher in the SensoriMotor Research group under the direction of Dr. Stephen Helms Tillery in the School of Biological and Health Systems Engineering at Arizona State University. I am conducting a research study to understand how sensory feedback is used during grasping and manipulation of objects.

I am inviting your participation, which will involve participating in one or more experiments, each lasting 30 minutes to 2 hours. During these experiments, you may be asked to touch or grasp a variety of objects and make a judgment about their size, texture, position, or other physical feature. In some cases, you will be asked to interact with objects in a virtual reality environment, using motion tracking markers and/or small vibrators placed on your hand and arm. You have the right not to answer any question, and to stop participation at any time.

Your participation in this study is voluntary, there is no compensation being offered for participation. If you choose not to participate or to withdraw from the study at any time, there will be no penalty. You must be 18-65 years old and without known neurological disease to participate in this study. There are no foreseeable risks or discomforts to your participation.

Your responses will be confidential. No personal information will be collected or linked to the data obtained during this research. The results of this study may be used in reports, presentations, or publications but your name will not be used.

If you have any questions concerning the research study, please contact the research team at: Stephen Helms Tillery, (480) 965-0753, stillery@asu.edu. If you have any questions about your rights as a subject/participant in this research, or if you feel you have been placed at risk, you can contact the Chair of the Human Subjects Institutional Review Board, through the ASU Office of Research Integrity and Assurance, at (480) 965-6788. Please let me know if you wish to be part of the study.

By participating in the research session you are agreeing to be part of the study.