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Environment Discrimination with Vibration Feedback to the Foot, Arm, and Fingertip

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Abstract— **Haptic feedback for upper-limb prostheses is desirable to enable a user to interact naturally with his or her environment, including operating the limb without vision and performing activities of daily living. We present a noninvasive method of providing one type of haptic feedback, vibration, to an upper-limb prosthesis user to enable discrimination of environment properties. Using a telemanipulation system that emulates an ideal prosthesis, able-bodied subjects tapped on materials of varying stiffness while vibration signals were recorded using an accelerometer. The vibrations were displayed in real time to the user through a C2 tactor mounted on the fingertip, foot, or upper arm. A three-alternative forced choice experiment was conducted, in which pairs of materials were presented. The subjects identified the stiffer surface or stated that they were of equal stiffness. Differing visual and force cues among the materials were eliminated through the use of the teleoperator and a graphical display. Results for five users indicate that vibration feedback to the foot enables environment discrimination comparable to that of the fingertip, and that the foot is better than the upper arm. The foot is a promising location for haptic feedback because of its sensitivity to haptic stimuli and the convenience of placing small devices and power sources within the shoe.**

I. Introduction

The goal of an upper-limb prosthesis is to allow a user who has lost part of the hand or arm to manipulate and sense his or her environment with the same ease as with an unimpaired limb. However, with existing commercial prostheses, much of the haptic sensation is lost. Users of upper-limb prostheses receive only general awareness of their artificial limb's position in space, as well as bulk forces that are felt at the socket. Fine details such as the perception of material properties are lost.

A major goal of the upper-limb prosthetics research community is to be able to send haptic information naturally through the nervous system so that the artificial hand may be incorporated into the user's sense of self. However, the current state of technology and brain understanding does not permit this direct feedback for the multiple degrees of freedom and many tactile sensations that exist in an unimpaired limb. We can, however, sense haptic information at the prosthetic arm and present it at a different body location using a noninvasive interface. In this paper, we describe the design and experimental evaluation of a haptic system that conveys environmental properties using vibration feedback to the foot, and compare it against vibratory feedback to the upper arm and fingertip. The system (Figure 1) uses a teleoperator to mimic ideal control of an upper-limb prosthesis for unimpaired subjects.

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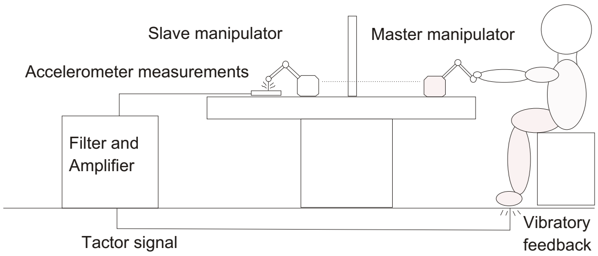

Fig. 1. Overview of the experimental setup. The user provides a motion input, sensory information is captured, and feedback is provided through natural proprioception and artificial vibratory feedback at specified locations on the body.

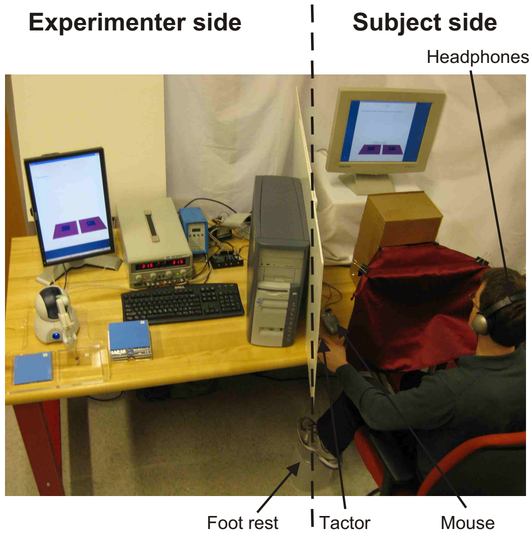

Fig. 2. Experimental setup. The user sits on the right side and interacts with a master manipulator (covered by a cloth) and mouse. Feedback is provided visually on the computer screen and haptically by a C2 tactor.

II. Background

A. Foot Haptics

The use of the foot as a haptic display location is of great interest because of its symmetric construction to the hand. Like the palm of the hand, the sole of the foot has glabrous skin, providing a greater bandwidth of sensory perception than other surrogate haptic sites (chest, trunk, upper limb, etc.). The glabrous skin is densely innervated by Meissner and Pacinian corpuscles, which are sensitive to vibratory stimuli. Clinical results show the foot's utility as a hand surrogate. Reconstructive surgeries have had fair success with using toe flaps to return sensory perception to mutilated fingers (e.g., [1]). Even so, some studies do not support use of the foot as a surrogate for the hand. Lin et al. [3] concluded that the vibratory threshold of the foot is higher than that of the hand. Kennedy and Inglis [4] suggested that the skin receptors in the foot sole have different behaviors than those in the glabrous skin of the hand.

Despite the differences between hand and foot physiology, we believe that the foot is an ideal place to feed back vibratory information. Of all the skin anatomical areas available to an amputee that have comparable sensitivities to the palm (the contralateral hand, feet, lips, and tongue), the feet present a large surface area for interface and offer a convenient option to package the feedback system inside a shoe.

Previous work has displayed both kinesthetic and cutaneous feedback to the foot. The HapticWalker [5] is a foot haptic device that simulates walking trajectories on different types of surfaces using kinesthetic feedback. Rovers and van Essen [6] developed a foot haptic device that provides vibratory feedback through more than eight tactors with the goal of enhancing non-verbal communication over a computer network. They used vibration motors with the ability to control 50 levels of intensity per channel and a bandwidth of 400Hz. Haptic insoles providing vibratory feedback were created to augment balancing abilities in the elderly population [7]. Kume et al. [8] provided vibration stimulation to the foot through a slipper-like interface. As a method of sensory substitution, Schoonmaker and Cao [9] transformed forces measured from a minimally invasive surgical instrument to vibrations fed back to the bottom of the foot. We are not aware of any study to date that has examined the display of material properties to the foot for prosthetics, although some research has considered the foot as a source of prosthesis control signals [10].

B. Vibration Feedback

Advantages of vibration feedback over conventional kinesthetic (force feedback) haptic devices include lower cost and power consumption, and increased maneuverability. However, the sensory feedback capabilities of vibration displays is limited, since resolved forces cannot be displayed. Vibratory feedback devices can be placed in an object held in the hand or attached to the body. When the vibrating element directly contacts the skin, these devices are referred to as tactors. In many research systems, such as virtual reality displays for combat and communication systems for pilots, multiple tactors are distributed over the surface of the body to display static or moving patterns. In consumer electronics, handheld vibration feedback is available in devices ranging from mobile phones to gaming controllers. The effectiveness of vibration feedback has been demonstrated in many systems; an overview of research in wearable vibration displays is provided by Lindeman et al. [11]. Providing vibration feedback to prosthesis users will be challenging for numerous reasons; it will require a clever tactor array design, vibratory mapping, control scheme, and packaging to successfully convey sensory information in real time, while not being cognitively taxing and annoying (due to the extended use). Here, we aim to show only that the foot is a reasonable location for transmitting the vibratory signals.

Our experiment is inspired by research on material discrimination using vibrations resulting from tapping or other contact transients. Kontarinis and Howe [12] and Wellman and Howe [13] investigated the use of tactile displays for conveying task-related vibrations in virtual and teleoperated environments, using a haptic display augmented with a voice coil motor to provide high-frequency vibrations. Okamura et al. [14] and Kuchenbecker et al. [15] developed virtual environments that displayed vibrations through the motors of a conventional kinesthetic haptic device, providing realistic contact transients that allowed subjects to identify different virtual materials. Kuchenbecker and Fiene [16] also demonstrated that the vibrations resulting from tapping can be predicted from material properties and impact velocity/acceleration. In all these systems, an accelerometer was used to acquire the vibration waveform. Although the displayed vibrations are not perfectly matched to the desired vibrations, the frequency content of the signals is sufficient to allow discrimination between very similar materials.

Vibration feedback has been used previously in prostheses, but only in sensory substitution scenarios. For example, in early work, Shannon [17] and Scott et al. [18] used vibratory feedback to convey grip/pinch force to the wearer of a prosthetic limb, and Mann et al. [19] used vibration to relay information on prosthesis elbow angular position. More recently, Pylatiuk et al. [20], Chatterjee et al. [21], and DEKA Research & Development Corporation (as described in the popular press) demonstrated that vibration feedback helps users control the grasp force of a myoelectrically controlled prosthetic device. In contrast to these force-to-vibration systems, the study in this paper considers a vibration-to-vibration mapping that transmits the signal sensed directly to vibratory feedback at the tactor.

III. Experimental Design

In this study, we investigate human discrimination ability during active exploration of the environment when vibratory feedback is made available to the fingertip, foot, or upper arm. The method of limits is used to quantify performance at each body site to identify the best location for providing vibration feedback. We are primarily interested in whether the foot would be an appropriate location for relaying sensory information to upper-limb prosthesis users.

A. Apparatus

An overview of our experimental setup is shown in Figure 1. A unilateral teleoperation system comprised of two haptic devices allows the user to explore a remote environment. Because the remote manipulator is controlled by user input, but the master provides no force feedback to the user, this system mimics the behavior of an ideally controlled prosthetic limb that can be used by unimpaired subjects. The user can control his or her motions actively to perform a task, yet receive cutaneous feedback only at specified locations.

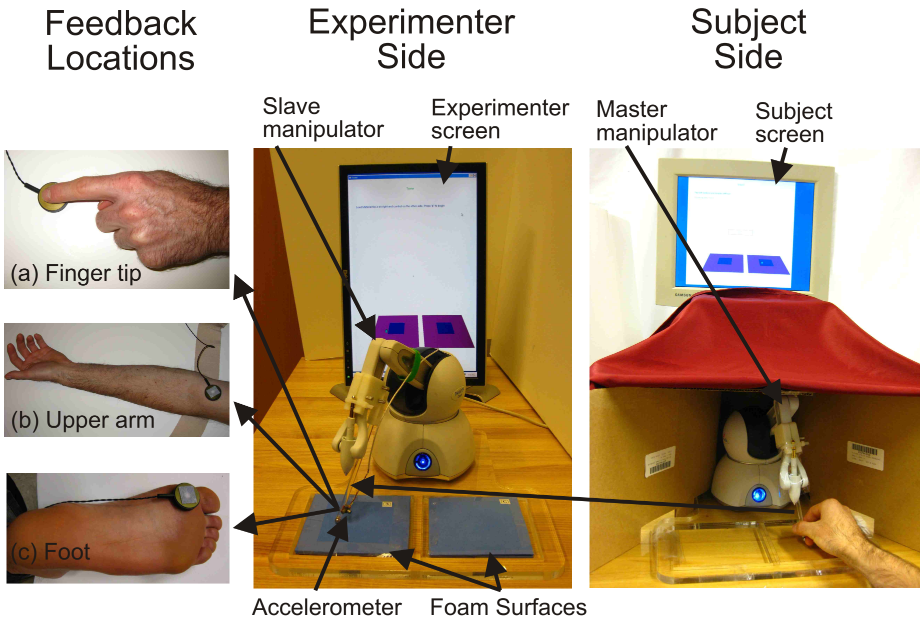

Fig. 3. Components of the experimental apparatus. Signals from the accelerometer are amplified and sent to a vibrating tactor placed on the foot, upper arm, or fingertip. At the left are the different conditions of vibration feedback; a C2 tactor is placed under the user's fingertip, or bandaged to the inside of the upper arm or the ball of the foot (bandage not shown). The tactor receives the vibration waveform to be displayed from an accelerometer mounted on a probe attached to the slave PHANTOM Omni, as shown in the center image. The subject uses the master PHANTOM Omni (shown at right) to control the motion of the slave in order to tap on the foam surfaces.

The experimental apparatus is shown in Figure 2, and the details are provided in Figure 3. The subject grasps the master manipulator (a PHANTOM Omni haptic device from SensAble Technologies, Inc.), which is modified to remove the last three rotational degrees of freedom, and holds the shaft of a rigid plastic probe. The subject observes a graphical display that provides a virtual representation of the remote environment (two surfaces for tapping) and the position of the end-effector of the remote manipulator (represented by a small sphere). Thus, the subject can see the motions he/she is making on the computer screen. Also available to the user is a computer mouse for response to experiment questions, a foot rest, and a vibration display (the C2 tactor from Engineering Acoustics, Inc.). The C2 tactor is a voice coil motor that is driven like a speaker with an output capacity of approximately 1 W. Unlike a speaker, the tactor is designed to transmit power well against skin impedance. The tactor has a diameter of 3 cm and a height of 0.8 cm.

The experimenter side of the apparatus includes the slave manipulator (a PHANTOM Omni identical to the master manipulator and modified to hold the same kind of rigid plastic probe), an experimenter screen, an accelerometer, and foam surfaces that represent environments with different material properties. The slave manipulator is controlled to follow the master using a proportional-derivative control law, with gains tuned for the most accurate tracking possible while maintaining stability. The teleoperation servo rate is 1 kHz, and data is acquired at 100 Hz. A Kistler accelerometer is mounted on the side of the probe with wax and is used to detect the vibrations generated by tapping the rigid stylus on the foam surfaces. The vibratory signal is filtered and amplified by a Kistler control unit with an empirically chosen low-pass filter cut-off frequency of 1 kHz and gain of 100 to give a clean and strong vibration signal at the hand. Seven distinct foam surfaces are used, as shown in Figure 4. Surface 0 consists of an acrylic base only, and surfaces 1 through 6 have the corresponding number of foam layers stacked on an acrylic base. Each acrylic base is 14.5 cm$\times$14.0 cm$\times$0.64 cm, and each foam layer has slightly smaller dimensions with a thickness of approximately 0.15 cm. The seven comparison surfaces, where 0 is the stiffest, are compared to a standard surface with three layers of foam (same as surface 3).

In the experiment, the subject controls the master manipulator to teleoperate the slave manipulator, so proprioceptive feedback from the arm and hand (as well as visual feedback from the screen) is present. Being a unilateral controller, no feedback is relayed to the user about the vibrations and forces sensed at the slave manipulator side. Layered on the teleoperator control is a linear-stiffness virtual wall implemented on the master manipulator to prevent the user from making motions that would damage the apparatus. As the probe makes contact with the surfaces, signals obtained from the accelerometer are modified by the Kistler control unit, sent through a voltage amplifier, and then transmitted to the user through the C2 tactor located either at the fingertip, upper arm, or foot. The C2 tactor was bandaged to the upper arm and foot, but for the fingertip condition the tactor lay on the table and the subject placed his or her finger over it.

B. Methods

This experiment was performed in one session lasting approximately 90 minutes. For each of the three feedback conditions (fingertip, foot, or upper arm), there were two

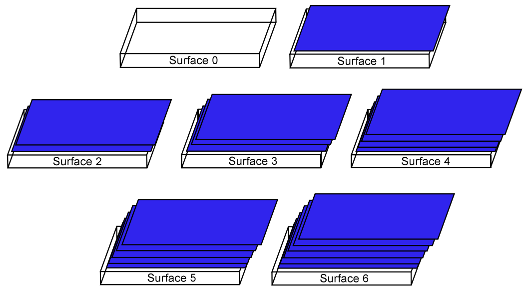

Fig. 4. Seven different surfaces are presented to the subjects. Surface 0 is an acrylic plate, and surfaces 1 to 6 have thin layers of foam mounted on the base acrylic plate. In the method of limits experiment, each surface is compared against surface 3.

practice sets and four experiment sets, with seven trials per set. Data was collected for all trials.

At the start of the experiment, each subject was seated comfortably next to the experimental set up with his or her right hand grasping the probe that is rigidly fixed to the master manipulator. The subject was instructed to grasp the plastic rod on the master device between the thumb and forefinger, and shown how to control the master device (and, in turn, the slave device) to make contact with the foam surfaces. The subject was then outfitted with the C2 tactor at a specified feedback location on the left side of the body (see Figure 3). The order in which the feedback conditions were presented was randomized for each subject. Next, the participant was informed how to use the visual display. The graphical representation renders the position of the slave device, and lets the subject know when contact has been made with the surface through a color cue. The subject was instructed to strike the center of the surface when tapping. The subject was given as much time as needed to practice controlling the master device and become familiar with the vibratory feedback.

The practice trials familiarized the subject with the experimental procedure. In each trial, the subject tapped on two surfaces (a standard surface and a comparison surface) for a mandatory 20 seconds, and then reported whether the left or right surface was stiffer, or the two surfaces were identical. The subject responded by clicking on the left, right, or center button of the computer mouse, respectively. In accordance with the method of limits, the comparison surfaces were paired up against the standard surface in their order of stiffness. The order of presentation of the comparison surfaces, ascending or descending stiffness, was reversed after every set. The location of the comparison surface (on the left or on the right) was randomized for each trial. For the first practice set (consisting of seven trials), the participant was informed of the correct response after the answer was reported. The subject then completed an additional practice set, this time wearing headphones playing white noise. Again, the subject was informed if an incorrect response was made.

Then the subject began the experimental trials. A thin curtain was used to cover the master manipulator and subject hand, and a white foam board was pulled out to isolate the subject from the experimenter. Visual feedback was only made available through a graphical display on the subject screen, and its primary function was to instruct the location where subjects should tap to keep the feedback as uniform as possible between trials and subjects. The participant wore headphones playing white noise to mask auditory cues. No feedback was provided on subject performance. A total of four experiment sets, or 28 trials, were completed for each subject.

This process of two practice and four experiment sets was repeated for each of the three feedback location sites. Upon completion of the testing, the subject was asked to fill out a survey, in which he or she reported general information such as age and gender, as well as ranked and qualitatively assessed the usefulness of each feedback location.

IV. Subjects

Approval was obtained from the JHU Homewood Institutional Review Board to collect data from human participants. There were five subjects, two female and three male, all of whom are dominantly right handed. Participant ages ranged from 21 to 29. From a self evaluation on experience with haptic devices, one participant reported no prior experience with a haptic device, three had participated in previous haptic experiments, and one was sufficiently familiar with the technology to program a haptic device. All subjects were healthy, reporting no neurological illnesses or health concerns. No compensation was provided.

V. Results

We now examine the experimental results to determine whether the foot is a feasible and desirable location to provide sensory feedback, with the goal of providing haptic feedback to upper-limb prosthesis users. Our preliminary findings support that vibrotactile feedback to the foot should be further pursued for this application.

A. Discrimination Results

Subjects tapped on seven unique foam surfaces (Figure 4). The acceleration profiles for three of these surfaces are shown in Figure 5. The frequency content is distinct for each surface; surface 0 exhibits the highest frequency content and surface 6 the lowest. The amplitude of the vibration waveform is unique for each trial because amplitude scales with impact velocity, and subjects are not able to precisely control their impact velocity for each tap.

For each trial, given the standard surface and one of the seven comparison surfaces, subjects reported which surface was stiffer, or if the two surfaces had equal stiffness. In Figure 6, we present a pictorial description (a modified confusion matrix) of the subjects' responses for each of the three feedback conditions. The results for all of the subjects' data combined, as well as for a representative subject, are displayed. The level of shading indicates the accuracy with which the subject was able to discriminate the surfaces from each other. Lightness indicates responses which were incorrect or when the response was that the two surfaces were equal (indistinguishable). Note that surface number 3

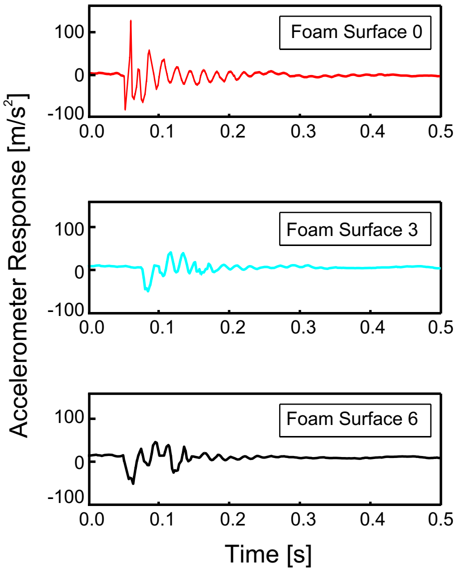

Fig. 5. Acceleration profiles for three surfaces with data collected at 500 Hz. This example data is provided for the standard surface (equivalent to surface 3) and the extremes of the comparison surfaces (surface 0, the stiffest, and surface 6, the softest). The impact velocities for the vibration waveforms shown were approximately 23, 27, and 29 mm/s, respectively.

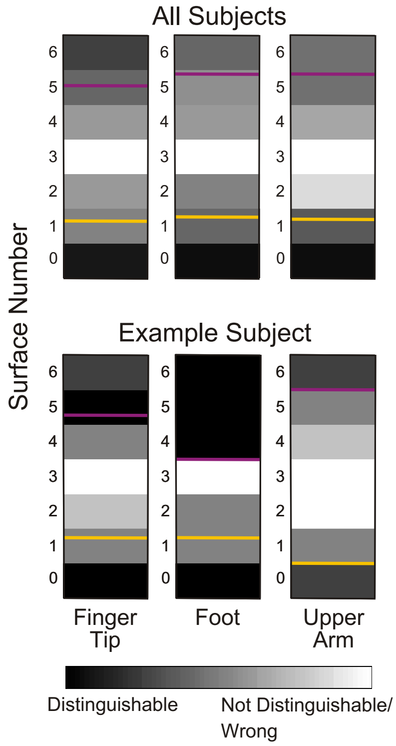

Fig. 6. User responses over the three feedback conditions: fingertip, foot, and upper arm. All Subjects summarizes performance for all of the participants, while Example Subject is the results for a participant who had additional training. A dark band implies that the stiffer surface could be successfully identified, whereas a light band implies that the surfaces could not be discriminated (because the surfaces where equal or the user response was incorrect). The stimulus levels at which subjects could discriminate 25% and 75% of the time are marked by respective purple and yellow lines.

must always be white. For perfect performance, we would have surface numbers 0, 1, 2, 4, 5, and 6 filled in black, and surface 3 white. Less white space implies that subjects are better able to discriminate at the given feedback location.

Additionally, the stimulus levels at which subjects could discriminate 25% and 75% of the time are marked by respective purple and yellow lines in Figure 6. The 25% location is determined by identifying where the subject changes from a less than response to an equal response for the first time, and likewise, the 75% location is calculated by identifying where the subject changes from a greater than response to an equal response for the first time. The respective percentages were averaged across all sets. A smaller distance between these locations indicates heightened discrimination abilities.

B. User Preferences

At the end of the experiment, each subject filled out a survey, in which they ranked the three feedback conditions in order of usefulness (1 is least useful, 3 is most useful), and commented on their reasoning for these rankings. The subjects' responses are summarized in Figure 7. Overall rankings were identical for the fingertip and upper arm, and better for the foot.

A Kruskal-Wallis one-way ANOVA was run to determine the impact of feedback locations on perceived usefulness. This is a nonparametric test equivalent to the commonly used one-way ANOVA. Significance was not found in the subjects' usefulness rankings ($\chi^2(2,12) = 3.33$, $p = 0.1896$).

VI. Discussion

With the goal of providing a more natural sensory experience to upper-limb prosthesis users, we have investigated the viability of the foot as a vibration feedback location. In this study, we designed an experimental apparatus that mimics the experience of controlling a prosthesis for unimpaired humans. The user makes an effort to control the motion of an arm, however, general haptic feedback of the remote environment is not provided. The feedback received by the subject is limited to real-time vibration information. Vibrations are measured by an accelerometer and transmitted to the user via a C2 tactor that is attached at a prescribed location on the body. We compared user performance in a material stiffness discrimination task when vibratory feedback was provided to the fingertip, foot, or upper arm.

Our findings suggest that the foot is a viable location for providing vibration feedback. Although vibration was the only cue to the users that differed between the surfaces, subjects generally performed the stiffness discrimination task very well. Results indicate that performance of vibration feedback to the foot is comparable to that of the fingertip, and for the Example Subject, we saw that the foot was even better than the fingertip (Figure 6). The upper arm exhibited the worst performance. These findings are in line with the literature on human sensing and perception; since both the fingertip and foot have glabrous skin, they are more sensitive to vibratory stimuli than the upper arm's hairy skin and, in turn, better performance is observed.

Feedback to the foot was also ranked by subjects as most useful, although running more subjects will allow us to

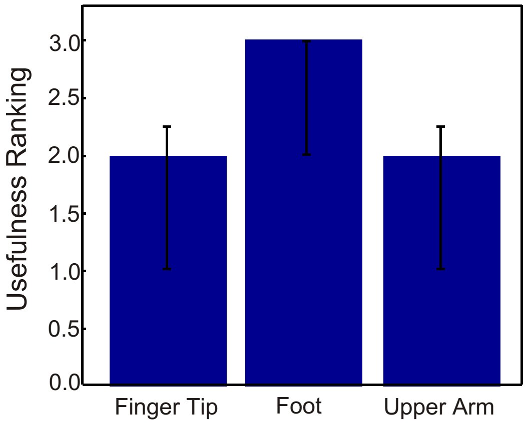

Fig. 7. Shown are the lower quartile, median, and upper quartile usefulness rankings for all of the subjects' data. A lower ranking indicates that the subject thought that feedback condition was more useful.

determine if this is significant. Anecdotally, training seems to have a significant effect on performance. Due to a lack of experience with haptic devices, the Example Subject used more training time than the other subjects, and his performance showed the most obvious differences between the three conditions. With more training and additional subjects, the results for the various conditions would likely be more distinct; this is planned for future work.

This study lays the foundation for future research on vibration feedback to the foot as a means for haptic feedback in upper-limb prostheses. From our initial results, we have shown that discrimination performance at the foot is comparable to the fingertip and upper arm, if not better. Beyond expanding the study presented in this paper, we plan to develop and evaluate practical vibration feedback systems that can be placed in a (modified) shoe. This includes developing new stimulation devices of appropriate size and cost, as well as understanding the performance of the system when a constant or time-varying load is applied to the foot (such as will occur when the user is standing or walking). It will also be necessary to understand how the user's knowledge of his/her hand or finger motion provides context for the vibration information. In our experiment, the subjects had near-perfect (natural) proprioceptive feedback and control of the manipulator, but in practice this will not be the case. It is clear from prior work that the shape of the vibration waveform is affected by the hand motion, including the impact velocity for tapping on surfaces and the lateral velocity when stroking textures. We can also test the effectiveness of our foot haptics approach in conveying material properties other than stiffness, such as roughness or texture.

Acknowledgements

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References

[1] N. Kimura and M. Saitoh, "Recovery of disused replanted digits by second toe hemipulp flap transfer," *Plastic and Reconstructive Surgery*, vol. 117, no. 2, pp. 507–513, February 2006.

[2] S.-H. Woo, G.-J. Lee, K.-C. Kim, S.-H. Ha, and J.-S. Kim, "Immediate partial great toe transfer for the reconstruction of composite defects of the distal thumb," *Plastic and Reconstructive Surgery*, vol. 117, no. 6, pp. 1906–1915, May 2006.

[3] Y.-H. Lin, S.-C. Hsieh, C.-C. Chao, Y. C. Chang, and S.-T. Hsieh, "Influence of aging on thermal and vibratory thresholds of quantitative sensory testing," *Journal of the Peripheral Nervous System*, vol. 10, pp. 269–281, 2005.

[4] P. M. Kennedy and J. T. Inglis, "Distribution and behaviour of glabrous cutaneous receptors in the human foot sole," *Journal of Physiology*, vol. 538, no. 3, pp. 995–1002, 2002.

[5] H. Schmidt, S. Hesse, R. Bernhardt, and J. Kruger, "Hapticwalker–a novel haptic foot device," *ACM Transactions on Applied Perception*, vol. 2, no. 2, pp. 166–180, April 2005.

[6] A. F. Rovers and H. A. van Essen, "Guidelines for haptic interpersonal communication applications: an exploration of foot interaction styles," *Virtual Reality*, vol. 9, no. 2-3, pp. 177–191, 2006.

[7] A. A. Priplata, J. B. Niemik, J. D. Harry, L. A. Lipsitz, and J. J. Collins, "Vibrating insoles and balance control in elderly people," *The Lancet*, vol. 362, pp. 1123–1124, October 2003.

[8] Y. Kume, A. Shirai, M. Tsuda, and T. Hatada, "Information transmission through soles by vibrotactile stimulation," *Transactions of the Virtual Reality Society of Japan*, vol. 3, no. 3, pp. 83–33, 1998.

[9] R. E. Schoonmaker and C. G. L. Cao, "Vibrotactile force feedback system for minimally invasive surgical procedures," *IEEE International Conference on Systems, Man and Cybernetics*, vol. 3, pp. 2464–2469, 2006.

[10] M. C. Carrozza, A. Persichetti, C. Laschi, F. Vecchi, R. Lazzarini, P. Vacalebri, and P. Dario, "A wearable biomechatronic interface for controlling robots with voluntary foot movements," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 1, pp. 1–11, 2007.

[11] R. W. Lindeman, Y. Yanagida, H. Noma, and K. Hosaka, "Wearable vibrotactile systems for virtual contact and information display," *Virtual Reality*, vol. 9, no. 2-3, pp. 203–213, 2006.

[12] D. A. Kontarinis and R. D. Howe, "tactile display of vibratory information in teleoperation and virtual environments," *Presence*, vol. 4, no. 4, pp. 387–402, 1995.

[13] P. Wellman and R. D. Howe, "Toward realistic vibrotactile display in virtual environments," *Proceeding of the American Society of Mechanical Engineers, Dynamic Systems and Control Division*, vol. 57, pp. 713–718, 1995.

[14] A. M. Okamura, M. R. Cutkosky, and J. T. Dennerlein, "Reality-based models for vibration feedback in virtual environments," *ASME/IEEE Transactions on Mechatronics*, vol. 6, no. 3, pp. 245–252, 2001.

[15] K. J. Kuchenbecker, J. Fiene, and G. Niemeyer, "Improving contact realism through event-based haptic feedback," *IEEE Transactions on Visualization and Computer Graphics*, vol. 12, no. 1, pp. 219–230, 2006.

[16] K. J. Kuchenbecker and J. Fiene, "Shaping event-based haptic transients via an improved understanding of real contact dynamics," *Proceedings of the IEEE World Haptics Conference*, pp. 170–175, 2007.

[17] G. F. Shannon, "A myoelectrically-controlled prosthesis with sensory feedback," *Medical and Biological Engineering and Computing*, vol. 17, no. 1, pp. 73–80, 1979.

[18] R. N. Scott, R. H. Brittain, R. R. Caldwell, A. B. Cameron, and V. A. Dunfield, "Sensory-feedback system compatible with myoelectric control," *Medical and Biological Engineering and Computing*, vol. 18, no. 1, pp. 65–69, 1980.

[19] R. W. Mann and S. D. Reimers, "Kinesthetic sensing for the emg controlled "boston arm"," *IEEE Transactions on Man-Machine Systems*, pp. 110–115, March 1970.

[20] C. Pylatiuk, A. Kargov, and S. Schulz, "Design and evaluation of a low-cost force feedback system for myoelectric prosthetic hands," *Journal of Prosthetics and Orthotics*, vol. 18, no. 2, pp. 57–61, 2006.

[21] A. Chatterjee, P. Chaubey, J. Martin, and N. V. Thakor, "Testing a prosthetic haptic feedback simulator with an interactive force matching task," *Journal of Prosthetics and Orthotics*, vol. 20, no. 2, pp. 27–34, 2008.