Sensory Feedback in Lower Limb Prostheses

Nataliya Rokhmanova

A thesis
submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Mechanical Engineering

University of Washington
2019

Committee:
Eric Rombokas, Chair
Katherine Steele
Santosh Devasia

Program Authorized to Offer Degree:
Mechanical Engineering

University of Washington

Abstract

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Nataliya Rokhmanova

Chair of the Supervisory Committee:
Eric Rombokas, Ph.D.
Affiliate Assistant Professor
Mechanical Engineering

Does the loss of limb necessarily entail the loss of sensation that limb provided? We argue that it does not. Targeted Reinnervation surgery provides a way to restore native feelings of sensation: it is an increasingly common procedure that can be leveraged to elicit phantom sensations, and we describe a method to characterize and make use of these sensations in the lower limb. Even without this surgery, it is still possible to provide amputees with a source of useful information as a supraphysiological source of sensory feedback. By developing and evaluating a prosthetic device for lower-limb amputees that uses vibration to provide sensory cues, we demonstrate improved confidence in foot placement during stair descent. This work aims to motivate and guide the development of lower limb prostheses with attention paid to sensation.

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ACKNOWLEDGEMENTS

This work was supported in part by the U.S. Department of Defense under Grant W81XWH-15-1-0417.

DEDICATION

“All we have ever created is heat.”

Chapter 1. INTRODUCTION

A prosthesis is a tool that is used as any other tool or limb, about which predictions of its behavior are generated. When using a tool, sensory data yields a rich space of information to sample from, resulting in a greater opportunity to refine and accommodate for prediction errors, and therefore to use the device with greater skill. In the absence of this sensory information, performance drops. Fingers that have been numbed by cold, cheeks after Novocain, or a cup full of water in the dark are troublesome to control.

Two questions guide this research: 1) Can someone use additional sensory information to perform a task with greater accuracy? and 2) How might we evaluate whether this additional sensory data is being taken up sensibly, e.g. whether it is useful, and to what to degree? This research is situated in application. As put by Maurice Merleau-Ponty in *Phenomenology of Perception*, “I cannot understand the function of the living body except by enacting it myself, and except in so far as I am a body which rises toward the world.” [1]. To understand the sensory function of the living body and to rise toward the world, we address these questions in the context of lower limb prosthetic devices.

The lower limb has largely been left out of the sensory discourse (Section 1.1) despite a wealth of research in the area of sensory feedback (Section 1.2). To address this gap, we will explain how we have developed and validated the use of a vibrating array to give information on foot placement (Chapter 2). Though these findings indicate that the use of vibrotactile feedback improves foot placement performance during stair descent (Chapter 3), the mechanisms underlying its usefulness are unclear, thereby preventing the customization of feedback that would improve an amputee’s experience of wearing their prosthetic limb. To systematically evaluate what external characteristics of this feedback may be modulated to improve perception, we identified the material properties of the feedback interface that elicit the greatest subjective response (Chapter 4). Rather than quantifying how the vibration is transmitted to the skin, we employed a psychophysical approach. However, if the ultimate aim of sensory feedback devices is to seamlessly integrate with the body, even with the best signal transmission to perception ratio, the feedback provided is to a location that is physiologically incongruous; vibration at the thigh is used as a proxy for pressure at the foot. Targeted Reinnervation surgery provides a means for non-invasive sensory feedback to create the illusion of sensation that is location-matched. If a stimulus is at the location it is expected to be, this lightens the mental processing required to associate the sensation provided with the expectation or meaning of that sensation. Characterizing the extent of sensory reinnervation (Chapter 5), and mapping referred sensation from a vibration stimulus (Chapter 6) is a step towards understanding whether somatotopic location influences the usefulness of a supraphysiological stimulus. In sum, this work establishes a foundation for the development of lower limb prostheses that make effective use of sensory feedback.

1.1 CHALLENGES ENDEMIC TO LOWER LIMB PROSTHESES

With the loss of limb comes not only the loss of function; the rich sensory experience of navigating the world is lost as well. Though great strides have been made in replacing sensation in missing upper limbs, development of sensory feedback in lower-limb prostheses has been largely stagnant. And despite these impressive advances in prosthetic technology, lower limb amputees still walk more slowly [2], more asymmetrically [3], and have a greater risk of falling [4] than their intact-limb counterparts. These challenges are due in part to the absence of proprioception and sensation of limb position [5]. In intact-limb individuals, the mechanoreceptors of the foot and muscles facilitate optimal gait and balance [6]. When the peripheral nervous system's function is disrupted or altogether absent, coordinated movement and the maintenance of gait patterns are negatively affected [7].

The restoration of sensory feedback after limb loss has been self-reported to be of highest priority to amputees [8]. Without the ability to detect pressure or shear on the bottom of the foot, prosthesis users must rely on the attenuated sensation of forces at the residual limb through the socket [9], or their intact senses, such as sight [10] or sound [11]. The use of haptics may restore the tactile or proprioceptive aspects of gait events or foot pressure patterns, with the goal of reducing abnormalities in dynamic task execution, thus sustaining mobility through long-term prosthesis use.

1.2 STATE OF THE ART IN SENSORY FEEDBACK

Though the restoration of native sensation after limb loss is not yet possible, myriad methods have been developed to address the absence of proprioception and sensation by providing artificial forms of sensory feedback. This research can be shown as situated along two axes (Figure 1.1). The horizontal axis addresses the way that feedback is given to the body: it ranges from the invasive, e.g. surgical, to the non-invasive. The vertical axis shows the characteristics of that feedback, from "sensory substitution" to "modality matching". The term "sensory substitution" can be thought of as stimulating a sense that is *different from* the original. For instance, an individual with visual impairment may use sensory substitution by using a white cane to aid in walking and detecting objects in their path. They take advantage of their intact sense of touch to overcome the impaired visual sense. "Modality matching", on the other hand, would be to provide a user feedback of the *same type* as the impaired sense. For example, an impaired sense of pressure on the hand could be communicated by providing pressure where there is no impairment, such as the upper arm.

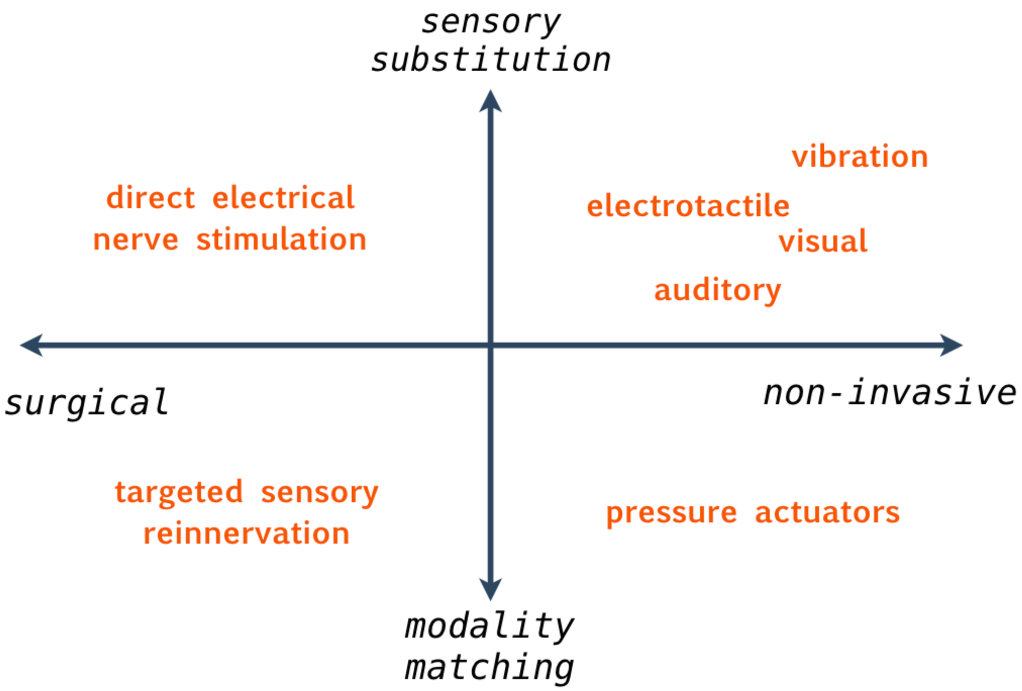


Figure 1.1. Established methods of providing sensory feedback, with selected examples at each quadrant.

Representative examples of sensory feedback at each quadrant begin at the top left and move counter-clockwise. Of the surgical methods, there have been some approaches to restore original nerve function after limb loss. A process called direct electrical nerve stimulation has been assessed, whereby electrodes are implanted in the peripheral nervous system to stimulate intact nerves [12].This induces haptic sensations in the missing limb, in the form of vibration or buzzing. This is an example of a surgical approach that uses a different sense modality than the original sense. As with all invasive surgical procedures, this method requires post-surgical care, and monitoring for long-term stability in light of rejection, scar formation, or system failure.

An alternate surgical approach in the modality-matched space is called Targeted Reinnervation (TR). TR is a post-amputation surgery where residual nerves are surgically redirected to innervate a different location of the body, which creates a map of sensation that is “referred” to the phantom limb. When a site on the reinnervated skin is touched, the individual feels a touch on their amputated limb [13]. These phantom limb sensations have been reported to be of a similar type as the sensation provided to the residual limb. However, this procedure is a patient-specific process. To the best of our understanding, these sensory maps cannot be extrapolated across subjects. In order to develop a sensory-enabled prosthesis, each TR recipient requires their own custom feedback system.

Research in the non-invasive space has been more common, likely because of the relative ease in study design and approval. All of the senses, except for taste, have been tested to evaluate sensory feedback in prostheses. An example of a feedback paradigm that is non-invasive and uses modality matching is a series of pressure actuators at the thigh. Fan et al. developed a thigh band for lower-limb amputees with an array of four silicone pneumatic balloons that would convey pressure to the thigh based on pressure at the bottom of the foot [14]. Though six intact-limb users were able to use the system with 95.8% accuracy to discriminate gait movements, the impact of this feedback on dynamic task performance is yet unclear.

Of the sensory substitution approaches, sensation can take the form of electrotactile, visual, auditory, or vibration feedback. Electrotactile stimulation is similar to the direct electrical nerve stimulation mentioned above. Here, the stimulation is superficial rather than invasive. A local electrical current at the skin can elicit feelings of tingling, itching, pressure or pinching, dependent on the voltage, current, waveform, size of the electrode and its contact with the skin, as well as the location on the body and the skin characteristics there [15]. The visual system has also been used as a means of feedback, such as the use of a visual computer display for measuring grasp force during an object manipulation task [16]. Auditory feedback has also been used in the upper limb, where the force of a grasp modulates the pitch, timbre, or volume of an audible beep [17].

Vibrotactile feedback in particular has been evaluated as a promising candidate for artificial sensory feedback. It is characterized by mechanical vibration of the skin. As compared to other types of non-invasive feedback, it appears most optimal. It is less prone to environmental interference than visual or auditory signals. Until the ubiquity of augmented reality glasses, it is portable, unlike visual feedback. It is also more comfortable for prolonged use than electrotactile feedback. Vibrotactile feedback has been previously used to provide feedback on center of pressure [18][19], the location of underfoot objects [20], as well as knee [21] and ankle flexion angles [22]. Cesini et al. validated the design of a belt-mounted vibrotactile system in a single unimpaired participant, for the aim of giving information on foot-ground contact when walking over ground or ascending/descending a ramp [23].

Some vibrotactile devices aim to provide a warning if some specific gait-related variable falls outside a certain range [24]-[26]. Others use biofeedback to train a particular mode of ambulation, feature of a dynamic task, or improve postural control [27]-[30]. The final type, and the one I investigate in the following sensory feedback paradigm, translates a characteristic of some gait event into a pattern of artificial stimuli, which the user can interpret as sensible meaning [14][31]. However, few studies have explored stair navigation; the effect of vibrotactile feedback on a lower limb amputee's performance using stairs has not yet been addressed.

1.3 STAIR DESCENT AS A TARGET TASK

Stair descent, which is a key part of rehabilitation and independent living, is a particularly challenging task for prosthesis users. By some estimates, 21% of lower-limb amputees can use stairs, and 32% do not use stairs at all [32]. Stair negotiation features many of the same difficulties of level-ground gait, requiring balance, a high degree of motor control and limb symmetry, and awareness of where the foot is placed. Added is the risk of trips and falls from a high elevation. Foot placement relative to the stair edge has been found to be a key determinant to safety, and optimal placement decreases the risk of falls [33]. However, the physical constraints of the prosthesis make optimal foot placement difficult.

Passive prostheses are generally aligned for stability during standing and smooth overground walking. The stiffness of the ankle, providing energy storage during the loading of the foot in stance, will induce unwanted forward propulsion during stair descent that may force the user down the stairs [34]. To compensate, amputees “roll” the foot over the edge of the step during descent [35]. This edge-rollover method is effective but requires the prosthesis user to visually confirm foot placement on the stair edge rather than relying on intact proprioceptive sensation. When amputees descend stairs, safe ambulation rests on their ability to know the position of their foot on the stair edge.

Chapter 2. DEVELOPMENT OF A SENSORY FEEDBACK DEVICE FOR STAIR DESCENT

To address the lack of sensation impeding a prosthesis user's ability to descent stairs safely, we can take advantage of the intact sense of touch elsewhere on the body. Here we describe the development of a vibrotactile feedback system that provides sensation to the user based on the position of the foot. It is a system for providing haptic feedback based on forces sensed at the insole, developed specifically to aid in stair descent (Figure 2.1).

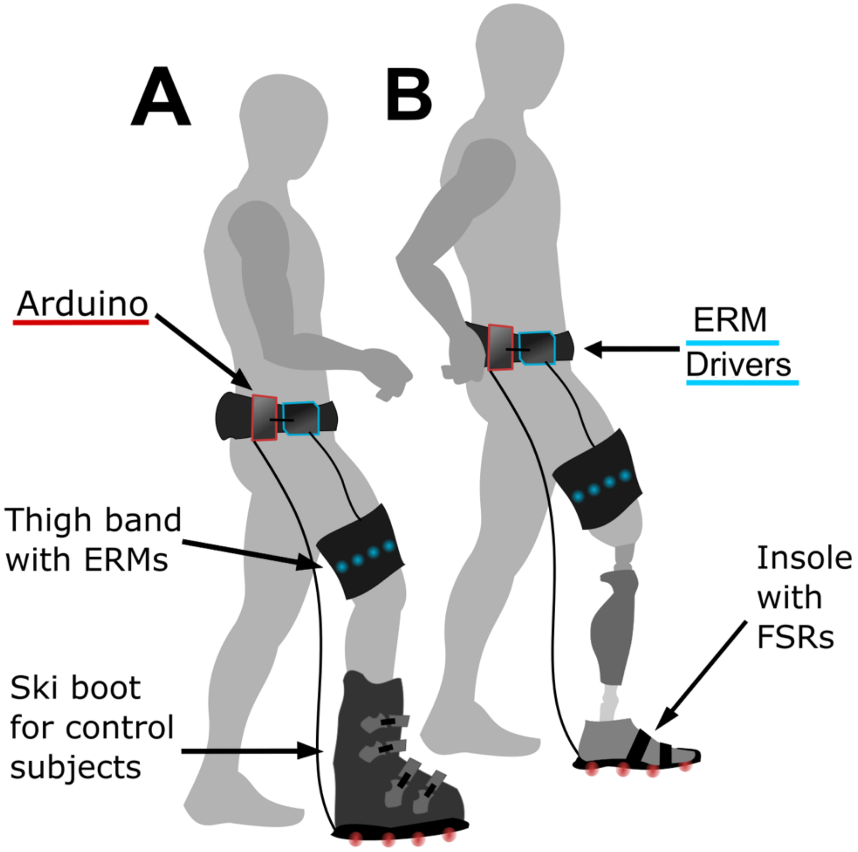


Figure 2.1. Sensory feedback device worn by a control participant (A) and below-knee prosthesis user (B)

2.1 REVISION TO EXISTING SYSTEM

The first prototype of this system was developed by Sie and Realmuto [36]. Plantar forces were read from an insole with four force sensors arranged from toe to heel. Logic and processing were executed with a BeagleBone Black system, which drove four piezoelectric motors at the thigh. The device was evaluated on intact-limb participants performing a stepping task while wearing a medical boot. Participants were asked to identify foot placement on the stair edge solely by relying on vibrations felt at the thigh.

However, the curved bottom of the medical boot prevented accurate readings of foot placement and did not eliminate the possibility of sensation through the boot. In this subsequent revision, the new system now makes use of a standard stiff ski boot with a flat sole for intact-limb participants. This eliminates plantar sensation felt through the boot and ensures full contact of all force sensors during a step. The fixed ankle and lack of plantar sensation of the ski boot ensures similarity to lower-limb prostheses.

The previous design used piezoelectric vibrotactors, which are potentially very expressive, but require custom drivers and are not commercially available. Here, coin eccentric rotating mass (ERM) vibrotactors are used instead for their ease in rapid system development. Finally, the powerful BeagleBone computing system is replaced with a lightweight, inexpensive and robust Arduino-based computing system.

2.2 SYSTEM DESIGN

The prosthetic feedback system consists of an insole, with four force sensors arranged from toe to heel, cueing vibration to four eccentric-rotating mass (ERM) motors worn medio-laterally on the thigh. The electronics for driving these vibrotactors are contained in a waist pack worn by the user. As illustrated in Figure 2.1, control participants wore the insole on the outside of a stiff ski boot with a flat sole, which has a fixed ankle and eliminates plantar sensation. This closely approximates prosthesis-wearing conditions. Prosthesis users don the force-sensing insole over their shoe.

2.2.1 *Force-Sensing Insole*

The insole is outfitted with four piezoresistive force sensors (FSRs), which communicate foot position on the stair edge upstream to the electronics driving the vibrotactors. The FSRs are arranged anterior-posterior, from toe to heel, and are kept in place by a plastic puck that is sewn down to the insole material. The puck does not trigger a force reading. FSRs are spaced 3.5cm apart. Control participants wore the insole on a stiff ski boot to simulate a prosthetic foot with limited dorsiflexion and lack of plantar sensation. All participants wore the same left ski boot. Prosthesis users wore the insole over their daily-use prosthetic foot, secured by Velcro straps over an athletic shoe (Figure 2.2).

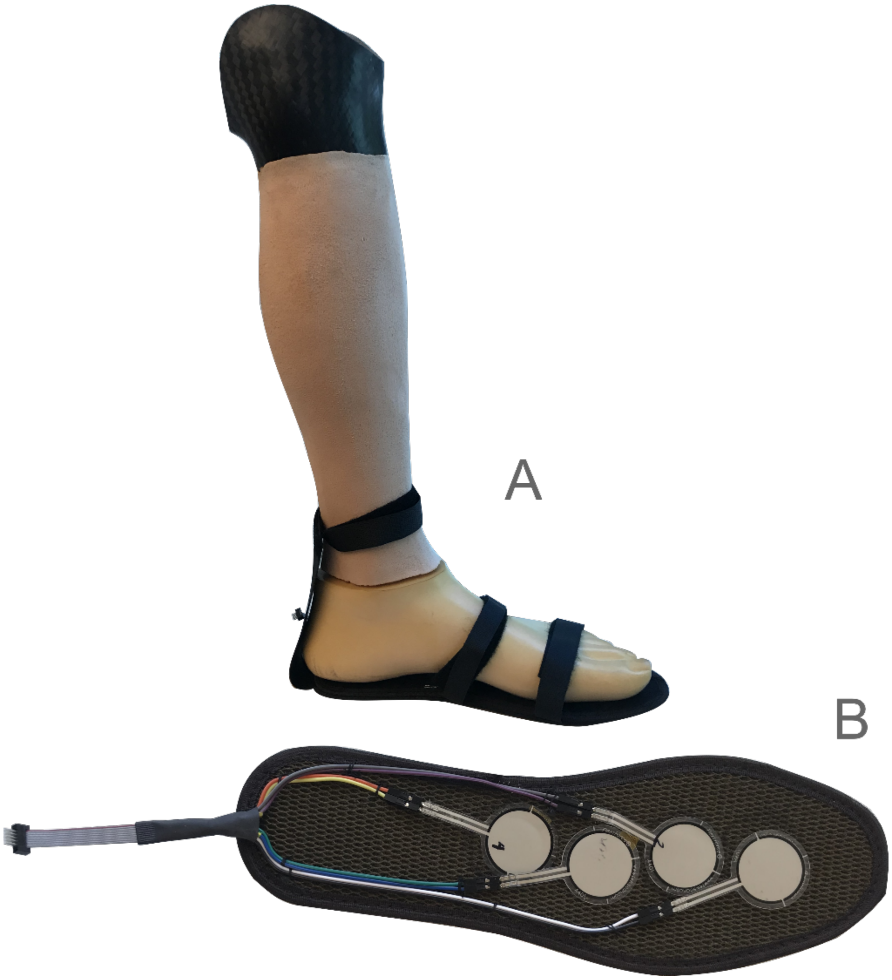


Figure 2.2. The force sensing insole, shown attached to a prosthesis (A), has four force sensing resistors (B).

2.2.2 *Haptic Thigh Band and Motor Housings*

A neoprene band with four vibrotactors attached in contact with the skin surface is worn across the thigh (Figure 2.3). The thigh was identified as an optimal location for vibrotactile feedback due to its surface area and proximity to the amputation site; validation of the system at the thigh also supports vibrotactor integration into a future prosthetic socket. Here, vibrotactors are arranged medio-laterally across the thigh. This arrangement is an artifact of the prior work, intended to allow for easier comparison of the data collected and assessing value of system improvements. Tactors are spaced 7cm apart to ensure discriminability.

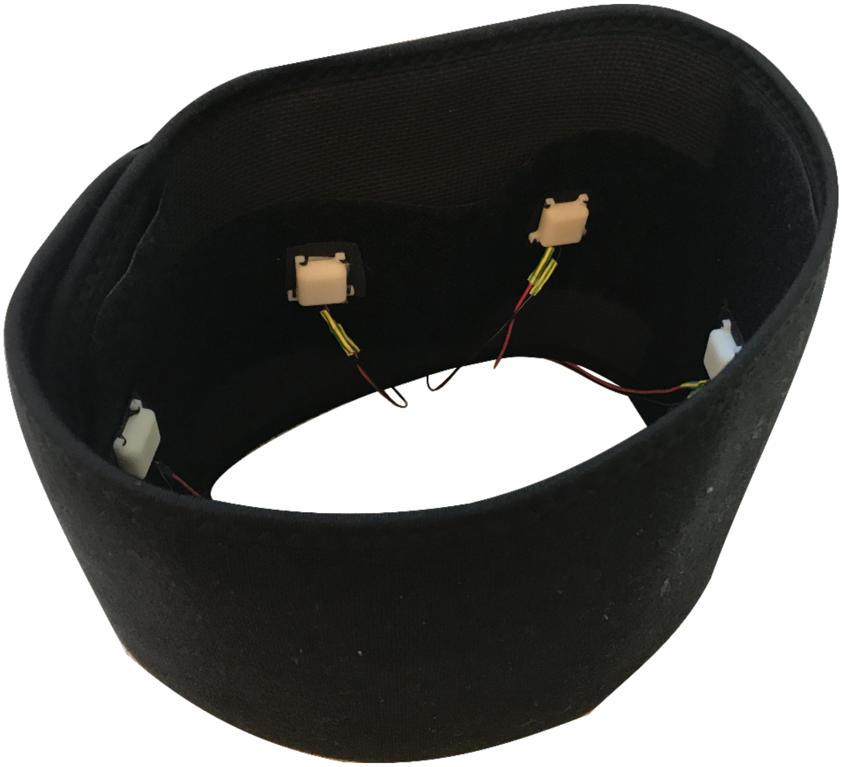


Figure 2.3. The haptic thigh band is worn by both experimental groups and fastens to fit with Velcro straps.

Vibrotactile stimulation was provided at 70Hz using the ERM, with a 2cm x 2cm skin contact area. Wentink et al. found this frequency to be appropriate for tactile simulation of the upper leg [37], thereby targeting the Ruffini and Pacinian corpuscles, responsible for detecting skin stretch and high frequency stimuli respectively [38][39]. Tactors are contained in an ABS housing with a smooth surface. More details on tactor housing design are provided in Chapter 4. Each tactor vibrates corresponding to a single FSR when it senses a force that has exceeded a hand-tuned threshold (Figure 2.4).

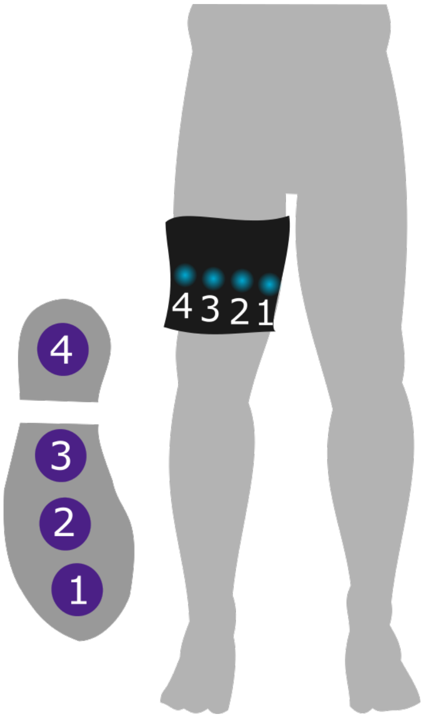


Figure 2.4. The orientation of the vibrotactors on the thigh band correspond to the orientation of the force sensors on the insole.

2.2.3 *Electronics*

An Arduino Uno computing system was used to relay force readings and cue tactor vibration. ERM vibration was cued to the tactor driver via I2C bus. Readings were collected from the FSRs at 10Hz. Sharma et al. investigated delay in limb motion given vibration stimuli applied to the thigh, and found that average response time was 0.8 seconds, with response accuracy greater than 90% [40]. At 10Hz, readings are sampled every 0.166 seconds, which is a sufficient sample rate for providing vibration feedback to the thigh. The electronics are contained in a waist pack worn by the user (Figure 2.5).

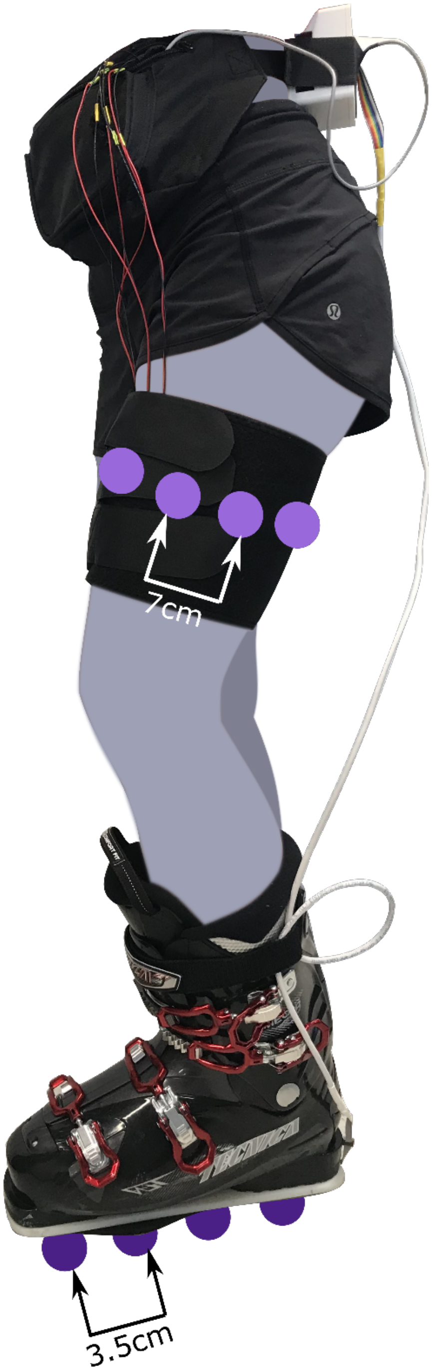


Figure 2.5. Complete experimental set up worn by a control subject, with spacing of vibrotactors and force sensors on insole indicated.

2.2.4 *Data Collection*

A wired connection from the Arduino Uno to a desktop computer was used to collect data via Robot Operating System (ROS) [41], with the Arduino serving as a ROS Serial node. De-identified data were collected and stored on the desktop computer before processing. In a later revision, a laptop computer was used in place of the desktop.

Chapter 3. EVALUATION OF SENSORY FEEDBACK DEVICE FOR STAIR DESCENT

In order to determine the utility of this type of sensory feedback to foot placement during a stair stepping task, the built device was evaluated in two conditions. Task 1 was an evaluation of a user's ability to discriminate individual vibrations of tactors. Task 2 was a simulated stair stepping condition that sought to evaluate the user's ability to use the vibrotactile feedback to infer the position of the foot off the edge of a step.

The vibrotactile feedback device has been evaluated on 17 participants in total. 12 control participants (8 male, ages 19-30) and 5 unilateral transtibial prosthesis users (5 male, ages 45-58) completed Task 1; 10 control participants (8 male, ages 19-30) and 4 unilateral transtibial prosthesis users (4 male, ages 45-58) completed Task 2. All participants consented under IRB approval.

3.1 TASK 1: INDIVIDUAL TACTOR DISCRIMINATION

The aim of Task 1 was to determine an individual's ability to accurately discern the vibration of individual tactors on the haptic thigh band. Adequate performance in Task 1 signified the validity of the experimental design, confirming that the vibrotactor spacing and vibration amplitude are sufficient for perception.

3.1.1 *Task 1 Experimental Methods*

The participant was seated comfortably and donned the haptic thigh band and noise cancelling headphones (Figure 3.1). The thigh band was oriented consistently across participants such that tactor 1 was on the anterior thigh. The experimenter indicated to the participant the location of the individual tactors, and cued a vibration to each tactor two times, stating the number of the tactor at each location. After this brief introduction, the discrimination task would begin.

The experimenter, out of sight of the participant, cued 1 of 4 tactors to vibrate in a pseudo-randomized order. The participant would verbally indicate the number of the tactor they felt vibrating. In 120 total trials, broken into three blocks of 40 trials, each tactor was cued with equal frequency. Participants were given a two minute break between blocks.

Performance in Task 1 was quantified by accuracy in localizing the correct vibrating tactor. A high accuracy would indicate that the vibration amplitude and spacing of tactors are sufficient for perception.

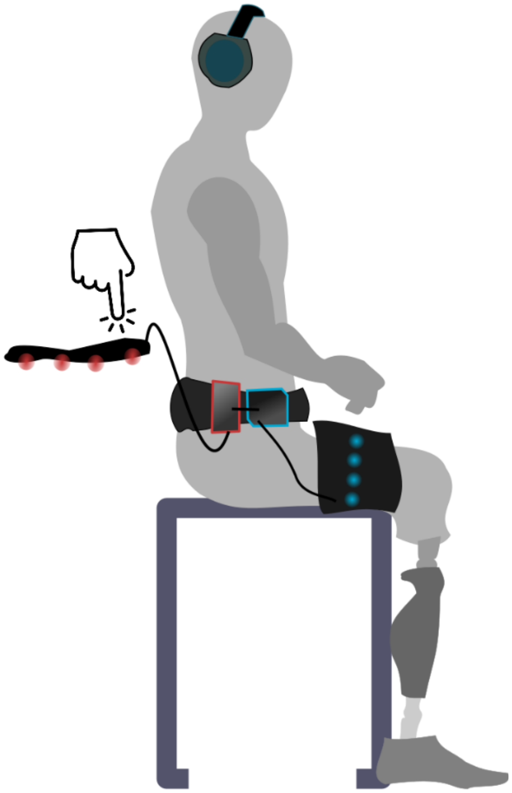
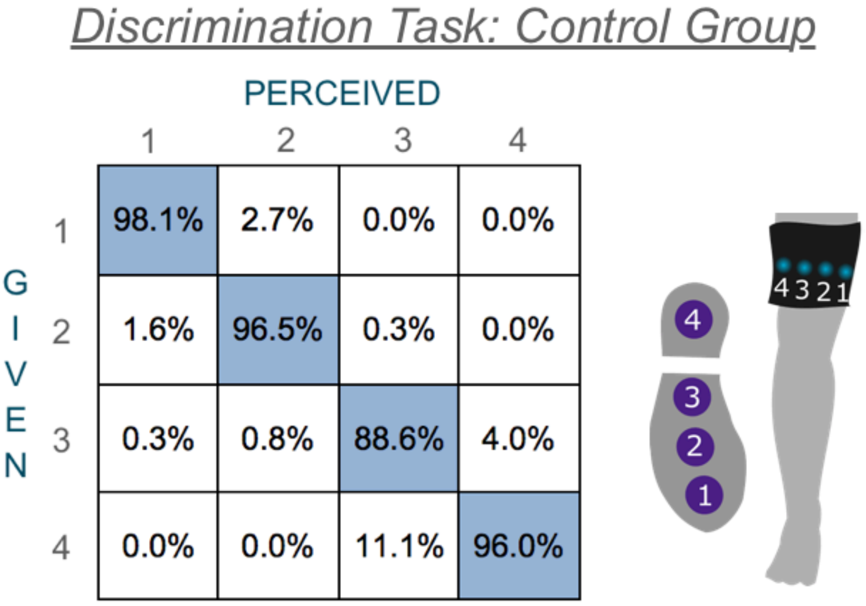


Figure 3.1. An image of the experimental setup for Task 1.

3.1.2 *Task 1 Results*

12 control participants (8 male, ages 19-30) and 5 unilateral transtibial prosthesis users (2 male, ages 53-58) completed Task 1. Response accuracy was calculated as the percent of correct responses out of 120 total trials. Accuracy of the 12 control participant responses ranged from 91.6% to 99.1%, with a mean of 95.4% and $\sigma = 2.87$. The average accuracy for each tactor location is shown in confusion matrix format in Figure 3.2.



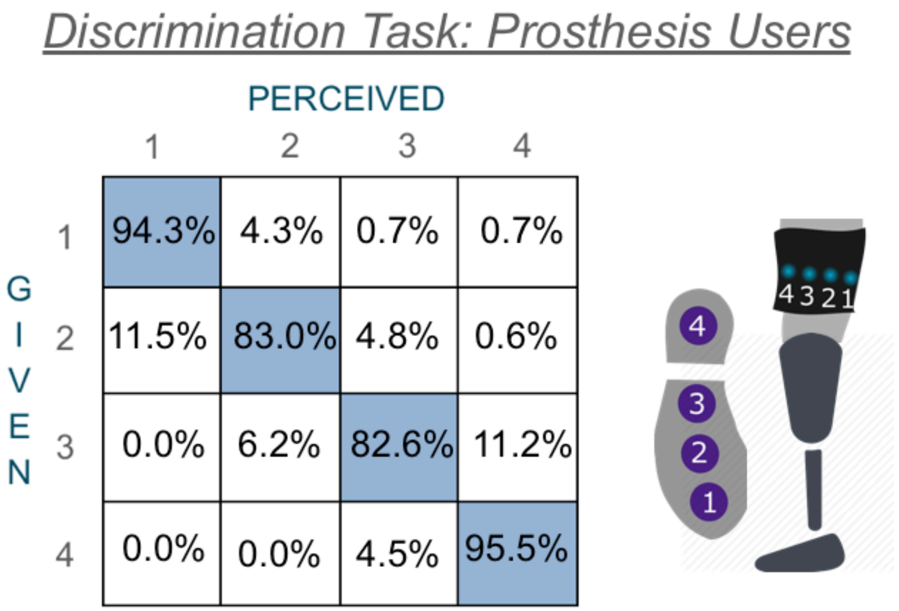
Discrimination Task: Control Group

PERCEIVED

GIVEN	1	2	3	4
1	98.1%	2.7%	0.0%	0.0%
2	1.6%	96.5%	0.3%	0.0%
3	0.3%	0.8%	88.6%	4.0%
4	0.0%	0.0%	11.1%	96.0%

Figure 3.2. Averaged responses in individual tactor discrimination (Task 1) for N=12 control participants. Accurate responses are on the diagonal.

The 5 prosthesis wearing participants identified the correct tactor with 88.9% average accuracy in sum. The average accuracy for each tactor location is shown in confusion matrix format in Figure 3.3.



	1	2	3	4
1	94.3%	4.3%	0.7%	0.7%
2	11.5%	83.0%	4.8%	0.6%
3	0.0%	6.2%	82.6%	11.2%
4	0.0%	0.0%	4.5%	95.5%

Figure 3.3. Averaged responses in individual tactor discrimination (Task 1) for N=5 transtibial prosthesis users. Accurate responses are on the diagonal.

In the control group and in three of the prosthesis users, accuracy was highest in identifying the most anterior tactor. These data support the findings of Wentink et al. that the anterior region of the thigh has greater sensitivity and specificity than the posterior [37]. One of the prosthesis-wearing participants had a much lower average accuracy, especially in determining the vibration of tactor 1. This is likely due to the participant's self-report of localized neuropathy in this area. Overall, the performance in Task 1 indicated that the vibration amplitude and tactor spacing were adequate for accurate perception.

3.2 TASK 2: FOOT PLACEMENT

In Task 2, participants were asked to discern the vibration of tactors during a stair stepping task on an experimental stair. The participant stepped down onto the stair edge, which was blocked from their view. One or several tactors would vibrate based on the position of the foot, as determined by the plantar force sensors. The participant would indicate the position of the foot on the edge of the stair based on which tactors they felt vibrating.

3.2.1 *Staircase Build*

An experimental staircase (Figure 3.4) was built to simulate a stair-stepping condition in a controlled environment. A prior staircase build by Sie was used as a structural guide, now with added components for stability and safety. The staircase had a sliding step hidden under an opaque sheet. The experimenter controlled the position of the step, out of sight of the participant, such that the stair edge lined up with one of four marked distances, corresponding to the four force sensors on the insole. The marked distances were spaced identically to the 3.5cm spacing of FSRs on the insole. A traced outline of the foot was marked in tape, indicating to the participant their target foot placement.

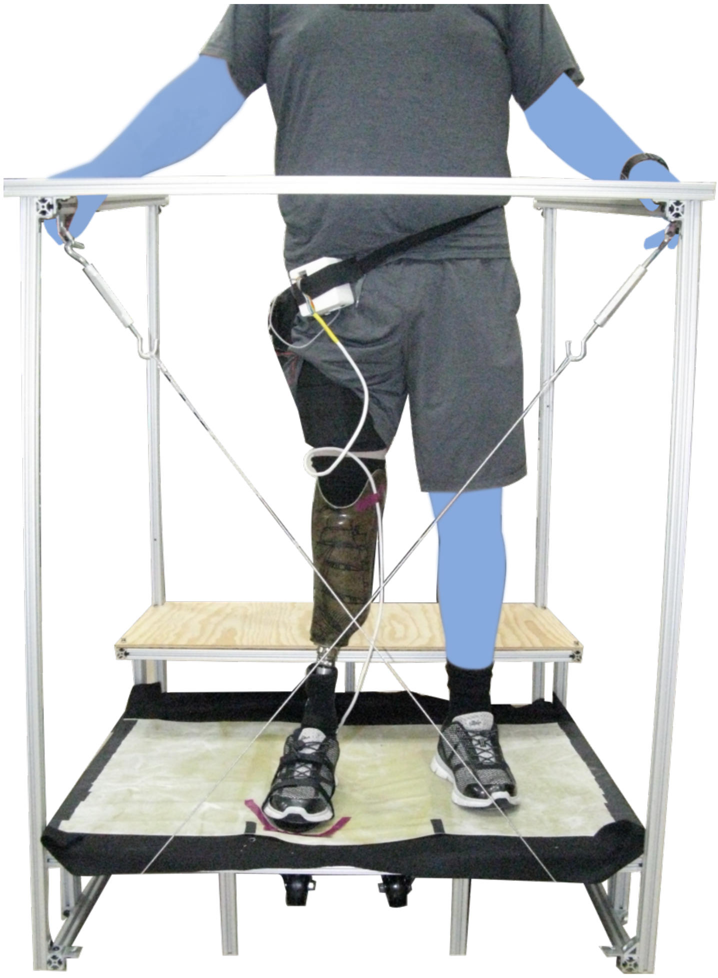


Figure 3.4. A transtibial prosthesis user shown standing with their right foot on the hidden step of the experimental stair. The foot was always placed in the traced outline, and the position of the hidden step was adjusted by the experimenter in order to activate the target FSRs.

3.2.2 *Task 2 Experimental Methods*

Participants donned the thigh band, the ski boot with insole or the insole over their shoe, and noise-cancelling headphones. They were instructed to stand with both feet on either side of the hidden step, marked with tape. Force sensor and tactor data were collected via a wired connection to a desktop computer throughout the course of Task 2.

Participants underwent a brief introduction to the experimental paradigm in the same manner as in Task 1. The experimenter moved the hidden step to one of the four positions, and instructed the participant to step down into the target outline. The experimenter confirmed that the placement of the foot cued the correct tactor vibrations using a live force-readout plot. Each of the four positions was presented to the participant twice, after which the stair stepping task would begin.

The tactors were numbered in the same order as in Task 1, with tactor 1 located at the anterior thigh. Stair position A, where only the FSR at the heel was activated, corresponded to vibration of tactor 4, at the lateral thigh. Position B, with half of the foot on the stair, corresponded to vibration to tactors 4 and 3. Position C corresponded to vibration at tactors 4, 3 and 2; position D, with the whole foot on the stair, corresponded to vibration of all four tactors.

The experimenter, out of sight of the participant, moved the stair to one of four positions in a pseudo-randomized order. The experimenter would cue the participant to step down. After ensuring their foot would land in the target location, the participant was instructed to gaze straight ahead so as not to receive accidental visual input on foot placement. 120 total trials were broken into 60 conditions with vibrotactile feedback, and 60 without. Blocks of 15 trials were presented in a counterbalanced repeated measures order, alternating between with-feedback and no-feedback, for 8 blocks total. Participants were given a two-minute break between blocks.

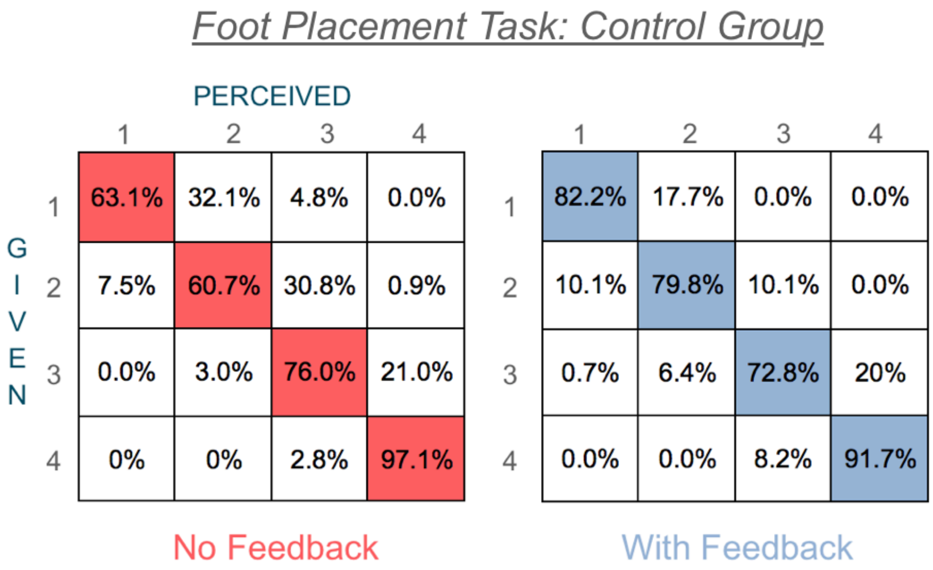
Performance in Task 2 was quantified by accuracy in reporting the correct position of foot placement. In the with-feedback trials, participants were instructed to report foot position based on vibration felt. In the no-feedback trials, participants were instructed to use the same proprioceptive strategy to estimate the position of the foot based on how far they felt their foot was overhanging the step. The data were post-processed to adjust for missteps, where accuracy was quantified based on actual tactor vibration rather than stair placement.

3.2.3 *Task 2 Results*

10 control participants (8 male, ages 19-30) and 4 unilateral transtibial prosthesis users completed Task 2. One prosthesis user was disqualified from participation in Task 2 due to their

use of an electrically powered socket (WillowWood LimbLogic) that elicited considerable vibration to maintain vacuum suction. The remaining participants used a standard mechanically-powered socket. Response accuracy for the vibrotactile feedback and no-feedback conditions were calculated as the percent of correct responses out of 60 total trials for each condition, after data post-processing (Section 3.2.2).

Of the 10 control participants, all but two showed improved accuracy with the use of feedback. Accuracy without vibrotactile feedback ranged from 53.3% to 88.3%, with a mean of 74.1% and σ =10.33. Accuracy with vibrotactile feedback ranged from 56.7% to 93.3%, with a mean of 82.5% and σ =10.39. Average accuracy for each foot position, both with and without feedback, is shown in confusion matrix format in Figure 3.5. Of the 8 participants who performed better with feedback, within-subject mean improvement was 15.0%.



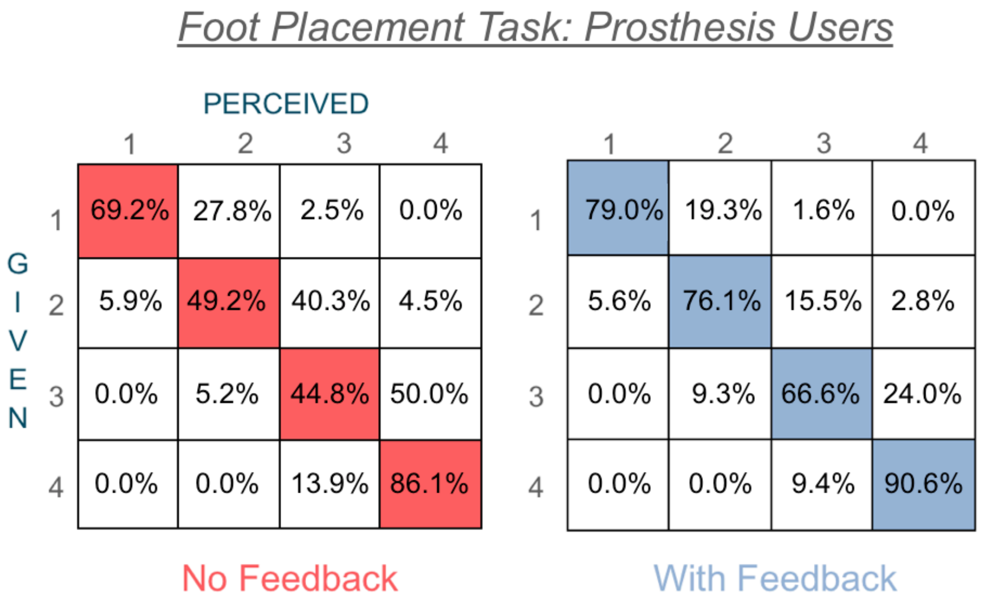
No Feedback	1	2	3	4
1	63.1%	32.1%	4.8%	0.0%
2	7.5%	60.7%	30.8%	0.9%
3	0.0%	3.0%	76.0%	21.0%
4	0%	0%	2.8%	97.1%

With Feedback	1	2	3	4
1	82.2%	17.7%	0.0%	0.0%
2	10.1%	79.8%	10.1%	0.0%
3	0.7%	6.4%	72.8%	20%
4	0.0%	0.0%	8.2%	91.7%

Figure 3.5. Averaged responses in foot placement (Task 2) for N=10 control participants without feedback (left) and with vibrotactile feedback (right). Accurate responses are on the diagonal.

In post-hoc discussion, the two participants who performed more poorly with the use of feedback reported that they found the vibration distracting. We suggest that these participants were unable to adjust to the cognitive load of the task, as the work of Husman et al. in evaluating perceptibility of haptic feedback found dynamic tasks to be more challenging than static tasks [42]. Additionally, several participants had experience wearing ski boots, and demonstrated a high baseline performance in determining the position of their foot on the stair edge from the experiment onset. Though these participants reported that they found the vibration useful, the task was not sufficiently challenging for their level of experience wearing ski boots.

All four prosthesis-wearing participants both showed improved accuracy with the use of feedback. One participant improved marginally, increasing accuracy with feedback by only 2%. However, their accuracy without feedback was the highest of the amputee group, and greater than one standard deviation away from the average amputee baseline. This participant would be less likely to benefit from additional sensory feedback, as they seem to already make robust use of their existing heuristics. For the prosthesis group, average accuracy for each foot position, both with and without feedback, is shown in confusion matrix format in Figure 3.6. Average within-subject improvement in accuracy for the prosthesis-wearing group was 10.1%.



No Feedback

	1	2	3	4
1	69.2%	27.8%	2.5%	0.0%
2	5.9%	49.2%	40.3%	4.5%
3	0.0%	5.2%	44.8%	50.0%
4	0.0%	0.0%	13.9%	86.1%

With Feedback

	1	2	3	4
1	79.0%	19.3%	1.6%	0.0%
2	5.6%	76.1%	15.5%	2.8%
3	0.0%	9.3%	66.6%	24.0%
4	0.0%	0.0%	9.4%	90.6%

Figure 3.6. Averaged responses in foot placement (Task 2) for N=4 prosthesis users without feedback (left) and with vibrotactile feedback (right). Accurate responses are on the diagonal.

On average, prosthesis users had a baseline without-feedback performance that was lower than that of the control group. This confirms that proprioceptive ability is diminished upon loss of limb. It is also possible that plantar sensation was not fully eliminated with a donned ski boot, giving the control participants a slight advantage in proprioception. However, these advantages are difficult to quantify: the awareness of the shank and knee in control subjects is of a different type than the prosthesis users' reliance on forces transmitted through the socket to the residuum.

Performance between Task 1 and Task 2 was lower in both experimental groups, likely due to the more physically and cognitively demanding nature of the second task. It did not appear that the simultaneous vibration of tactors posed a challenge to the control participants or to the more perceptive of the transtibial prosthesis users, as their average accuracy in identifying the vibration of a single tactor (tactor 4) was lower than in Task 1. Within-subject improvement in accurately detecting the position of the foot on the step was quantified as the difference between average accuracy without feedback and with feedback (Figure 3.7). Participants with low ability to discern foot placement without vibrotactile feedback showed the greatest increases in performance in the stair stepping task. As expected, this indicates that the feedback paradigm was most useful for those with lesser ability to identify foot position.

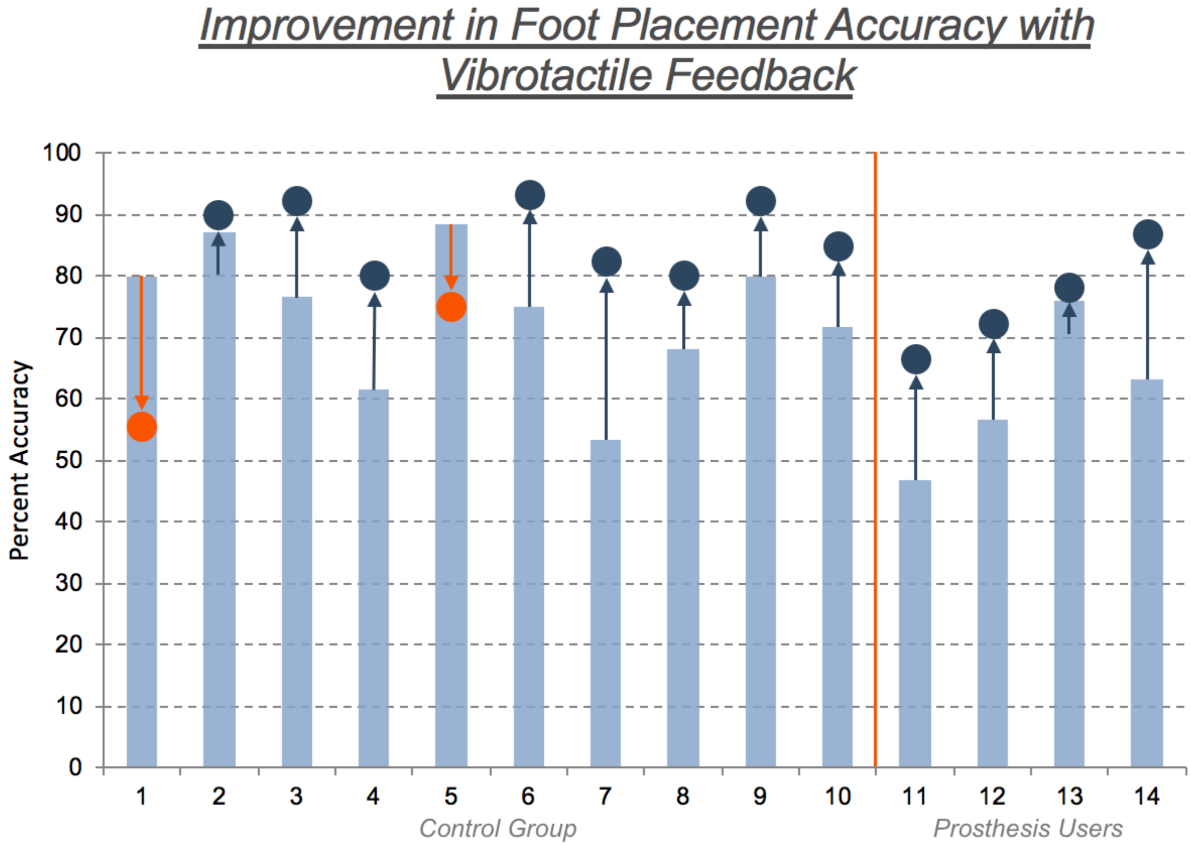


Figure 3.7. Within-subject improvement in Task 2 for all participants. Bars show accuracy without feedback, and dots show accuracy with feedback. Two control subjects displayed lower accuracy when using feedback (red dots).

3.3 SUBJECTIVE RESPONSES

Each participant wore the device for an average of two hours, and there were no complaints of discomfort. Prosthesis users responded favorably to the use of vibrotactile feedback. Prosthesis User 1 stated that the feedback was “like a secondary layer of confirmation, supporting what [they] already suspected about the position of their foot on the stair edge.” Prosthesis User 2 indicated that they preferred the vibration of multiple tactors simultaneously rather than localizing single tactors. Multiple tactors made discrimination "easier to identify than single motors, because I might get one that felt like it could be either [tactor] 1 or 2, but once I had 2 and 3 activated, I could isolate which one it was."

3.4 LIKERT-TYPE QUESTIONNAIRE

At the conclusion of the experimental procedure, participants were asked to respond to a 12 question Likert-type survey (TABLE I) to quantify subjective responses to the experimental setup and the haptic feedback device. Responses to an item on a Likert scale capture sentiment from strong agreement to strong disagreement. Here, we employ a 7-level scale, where a response of 1 corresponds to "strongly disagree", 4 is "undecided", and 7 is "strongly agree." Prompts were selected to be symmetrical, meaning containing equal numbers of positive and negative statements. To counteract acquiescence bias, the questionnaire consisted of paired positive and negative formulations of a question; ideally, numerical responses to contradictory prompts would be symmetrically opposite, indicating no bias. Prompts were also provided in randomized order.

TABLE I

LIKERT TYPE QUESTIONNAIRE PROMPTS

Evaluation of Experimental Setup:
During the experiment, I was able to hear external noises
During the experiment, I was completely isolated from hearing any outside noise
I felt comfortable in the experimental setup
The experimental setup was not comfortable
The haptic band sensation felt pleasant
The haptic band sensation felt unpleasant
Evaluation of Haptic Feedback:
It was easy to locate where the step was when I was not receiving haptic feedback
It was easy to locate where the step was when I was receiving haptic feedback
It was difficult to locate where the step was when I was not receiving haptic feedback
It was difficult to locate where the step was when I was receiving haptic feedback
I felt I performed better when receiving haptic feedback
I felt I performed better when the feedback was turned off

3.4.1 *Likert Responses to Experimental Setup*

Six prompts evaluated the experimental design for potential intervening factors. Discomfort in wearing the device or feeling the vibration feedback may have impacted a user's ability to perform without distraction. Any auditory interference or cues on hidden stair movement in Task 2 may constitute a biased response.

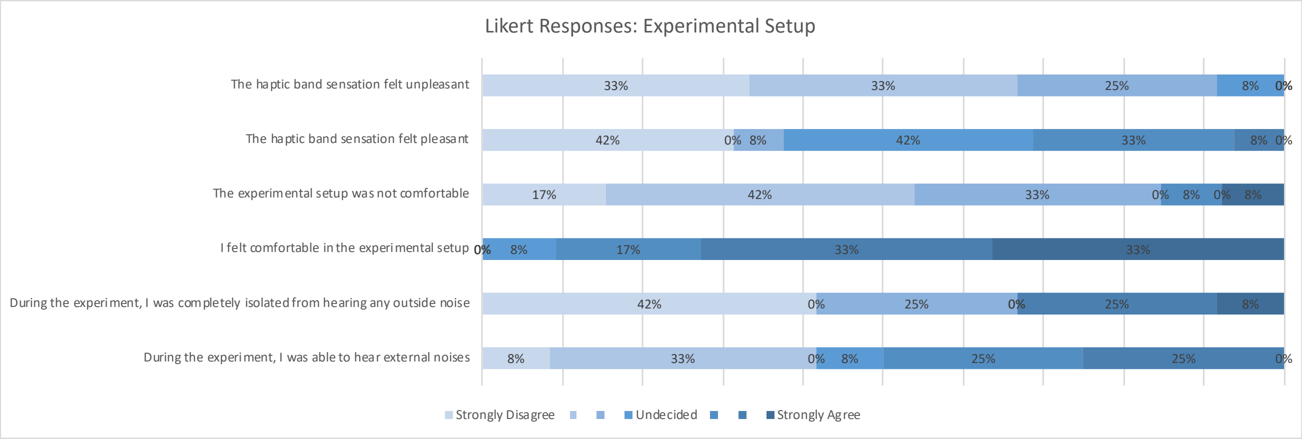


Figure 3.8. Likert responses to the design of the experiment. Users generally felt comfortable, but effect of outside noise may be of interest to further exploration.

Responses to these first six prompts show that the experimental setup was judged to be comfortable, and that the vibration feedback was not unpleasant. Some kurtosis is evident in how participants report their ability to hear outside noise. This may be due to a lack of clarity in how "outside noise" is defined, as some responders interpreted the ability to hear the experimenter's cues to step down during Task 2 as being a source of external noise. Regardless, subsequent studies ought to aim to reduce misunderstanding in interpretation, as well as to further remove potential for auditory interference. This may be done by providing headphones with white noise and transitioning to a non-verbal cueing system.

3.4.2 *Likert Responses to Haptic Feedback*

Responses to the haptic feedback device itself are of interest to device evaluation, as users are blind to the specific details of their performance when responding to the survey. Subjective judgment of their own abilities, and whether the device may aid or improve these abilities, will factor into whether a system of vibrotactile feedback will be readily accepted and consistently used by prosthesis users.

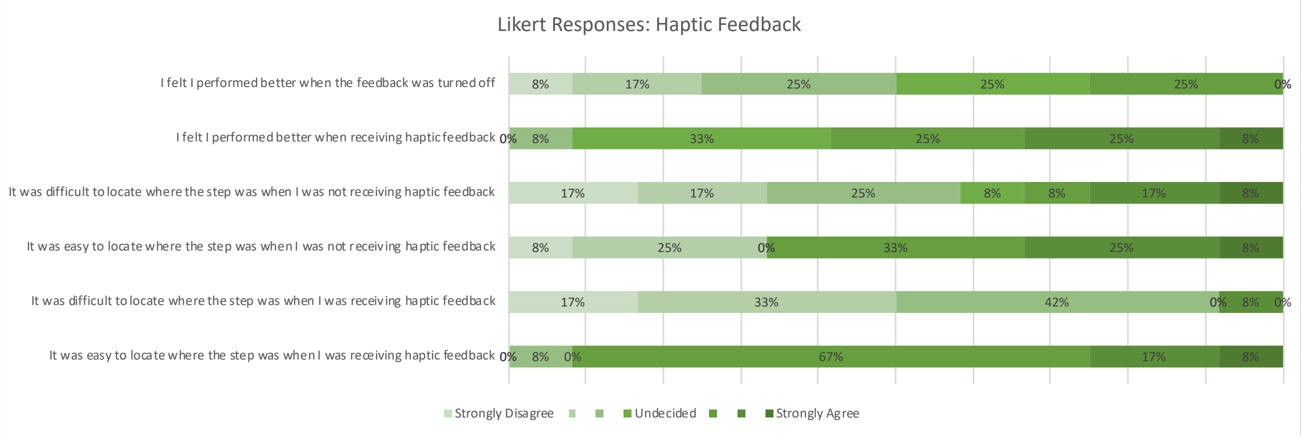


Figure 3.9. Likert responses to the haptic device. Though users report it being easy to locate where the step was without feedback, most agree that performance increases with feedback.

Control and prosthesis user responses to the feedback device were largely positive. These responses indicate that the device was perceived to be comfortable and suitable for daily use. Moreover, the users felt it improved their own ability to locate where the step was to a greater degree than previously possible without the use of the device. The questionnaire responses suggest that this vibrotactile feedback device is uniquely able to provide a daily-use mechanism by which users can perceive their surroundings more robustly, a benefit which has been heretofore absent.

3.5 DISCUSSION

In this study, we have demonstrated the implementation of a sensory feedback method that improves foot position perception during stair stepping, in control and prosthesis-wearing populations. We found that sensory feedback in the lower limb can be used to improve performance in a dynamic task. Naive participants can make use of this supraphysiological feedback paradigm, incorporating it into their sensory space and using it sensibly.

Vibration at the thigh as a proxy for pressure at the bottom of the foot may be an unintuitive sensory paradigm. In opposition to this claim, the successful use of vibrotaction at the thigh as a proxy for pressure at the bottom of the foot suggests the impressive plasticity of the sensory system in making use of a somatotopically and modality mismatched source of feedback. However, as our work was limited to only vibrotactile feedback, further study is necessary in order to evaluate observations that modality-matched (i.e. pressure) feedback is more effective for discrimination [43].

This method of sensory feedback may be well-suited for those that have undergone Targeted Reinnervation surgery. Development of a custom haptic prosthesis to induce referred sensation at the phantom limb would close the sensorimotor loop non-invasively, allowing the prosthesis to function as a highly integrated and more physiologically realistic replacement of the missing limb. This venture would allow for further exploration of the clinical and functional outcomes of providing sensory feedback to the lower limb.

Chapter 4. CHARACTERIZING THE SKIN TO MOTOR INTERFACE

Perception is an amalgam of neural processes at the central and peripheral levels. Developers of haptic feedback devices use their understanding of these processes to precisely tune how feedback is applied to the body, thus heightening its transmission and its effectiveness in acting as a sensory cue. Despite the wealth of knowledge on how vibration characteristics transmit information optimally, well-informed haptic design is currently stymied by the paucity of data on how the interface between tactor and skin serves to amplify stimulus perception.

This is a question of deep interest in the field of human-machine interfacing. Building a whole-body library of how material interactions influence haptic perception would be instrumental to designing performance-augmenting tools. We begin this venture within the context of our prior sensory work on providing feedback to the thigh.

The sensation-amplifying properties of a vibrotactor housing, e.g. the interface between skin and vibrotactor, have not yet been explored. Here, we determine the optimal vibrotactor vibration frequency, as well as housing surface area, material, and surface geometry that in tandem produce the most perceptible vibration to the thigh. Making optimal use of a biofeedback signal rests on ability to perceive the signal itself. As vibrotactile feedback becomes a standard integration in lower-limb prosthetic sockets, these findings may serve as a guide in designing for optimal perception.

4.1 VIBROTACTOR CHARACTERISTICS

Eccentric rotating mass (ERM) motors are a staple of rapidly prototyped wearable haptic devices. Though applying the vibrotactor directly to the skin is a suitable means of providing haptic feedback, exposing the electronics to the skin and sweat make this an impermanent solution for wearables. Enclosing the vibrotactor in a secure housing ensure longevity of the system. Here we systematically investigate how perception of haptic feedback depends on 1) vibration frequency, 2) compliance of housing material, 3) surface geometry and 4) contact area of the housing with the skin.

4.1.1 *Vibration Frequency*

Mechanoreceptors are skin receptors that are responsible for acknowledging vibration, pressure, temperature and texture. In the hairy skin of the thigh, Merkel disks and Pacinian corpuscles respond to mechanical stimuli. Merkel disks are a type of slowly adapting receptor, which respond continuously while a stimulus is present. They detect sustained pressure. Pacinian corpuscles respond to vibration, and are situated more deeply in tissue beneath hairy skin. At low frequency stimulation of hairy skin (less than 80Hz), the detection of vibrotactile input depends on hair follicle afferent fibers, and at high frequency (greater than 80Hz) depend on the deeply located Pacinian receptors [38].

The two sinusoidal vibration frequencies studied here were 250Hz, a common frequency for vibrotactile perception, and 70Hz, the frequency used in our previous studies on haptic feedback during stair descent.

4.1.2 *Compliance of Housing Material*

The vibrotactor housings were 3D printed on a polyjet Stratasys Object printer. We examined the effect of housing material on sensation by comparing a stiff PLA material (Objet Veromagenta, ShoreD hardness 76.1-81.7) and a compliant material (Objet Agilus30, ShoreA hardness 40-50) [44].

4.1.3 *Surface Geometry of Housing*

Three contact surface geometries were evaluated: a flat surface, convex hemispherical bumps, and radiating square waves (Figure 4.1). Quantity and spacing of both raised textures were also examined, of three types each.

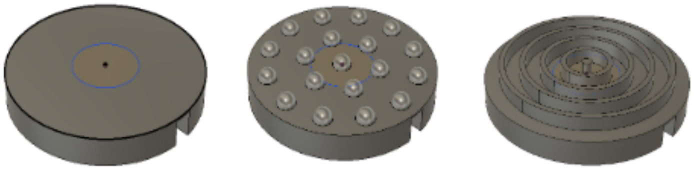


Figure 4.1. Tactor housings with a flat surface, convex hemispherical bumps, and radiating square waves.

Textured surfaces have been previously explored in active touch [45], wherein periodic textures have been found to propagate vibration during active touch. The intensity of vibration detected was shown to increase with the microgeometry of the surface. Based on the optimal grating dimensions found by Delhaye et al., a square wave housing was designed to radiate outward with the same dimension ratio. Figure 4.2 provides dimensions for the three types of square waves.

Spatial Period (SP) *[mm]*	**Ridge Width (RW)** *[mm]*	**Groove Width (GW)** *[mm]*	**Groove Depth (GD)** *[mm]*
3	0.75	2.25	2.25
4	1	3	3
5	1.25	3.75	3.75

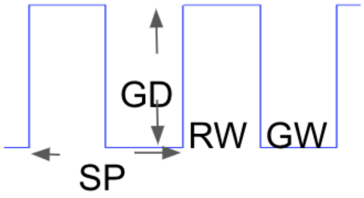


Figure 4.2. Dimensions of square wave housings.

The housing with hemispherical bumps was designed to investigate whether increasing surface area of material in contact with the skin without increasing the diameter of the contact area would impact perception. These housings have the hemispherical bumps equally distributed across the surface, such that the diameter of each sphere is equal to the distance between spheres.

4.1.4 *Contact Area of Housing*

The contact area of the vibrotactor housing to the skin has been previously shown to impact sensation. Lindsay et al. show that for larger areas of the body such as the thigh, at 250Hz maximum sensitivity occurs with a stimulation area of 5cm^2 [46]. This finding is supported by Gunther where sensitivity was found to increase with size: at 250Hz, optimal sensitivities were found at 5.1cm^2 and 2.9cm^2 when using a flat casing around a vibrotactor, with decreased sensitivity using contact areas of intermediate size [47]. From these two base areas, we extrapolated a third area at 7.1cm^2 to examine the effect of increased area on perception.

The total number of tactors evaluated was 42, as shown in Figure 4.3.

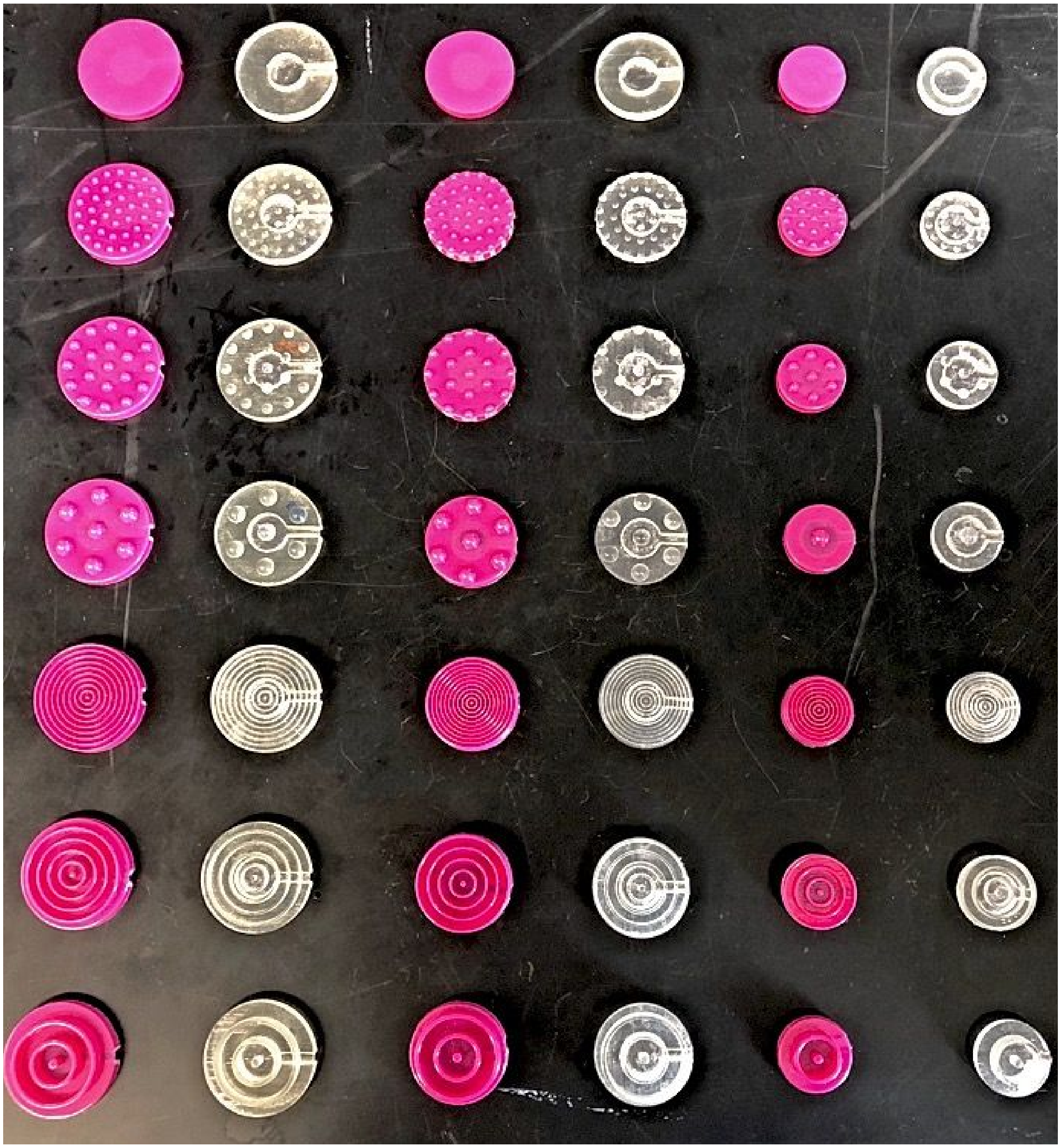


Figure 4.3. All 42 tactor housings, arranged in rows by surface geometry and in columns by contact area. The clear housings are printed in compliant material, and the magenta housings are printed in stiff material.

4.2 EXPERIMENTAL SETUP

A haptic evaluation device with interchangeable tactor housings was built to facilitate data collection. Identification of optimal material and configuration for the tactor housing was performed via the hierarchical alternative two forced choice test.

4.2.1 *Tactor Evaluation Device*

The tactor evaluation device developed to evaluate perception is shown in Figure 4.4. It consists of an interchangeable tactor module and is powered by an Arduino microcomputer. A force sensitive resistor is used to maintain constant pressure on the skin and to cue the vibration of the ERM. A half second vibration is triggered when the FSR exceeds a 6.5g threshold, ensuring consistent pressure, which has been linked to stimulus sensitivity [48]. However, in evaluating the effect of pressure on response accuracy of vibrotactile localizing, the effect of pressure was found to be non-significant [49].

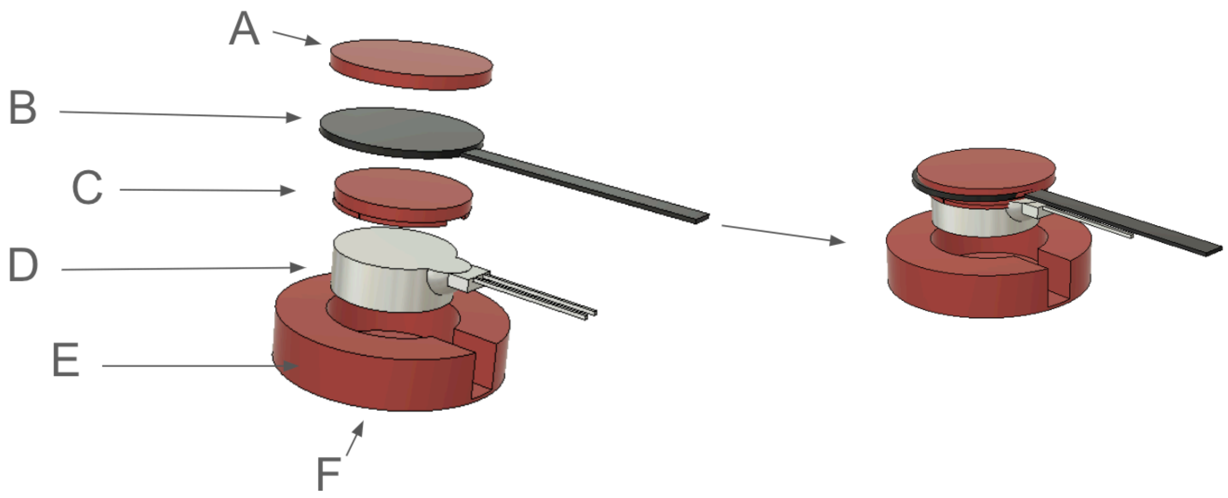


Figure 4.4. Tactor housing haptic evaluation device with a plate for distributing forces (A) read by the FSR (B). A cap (C) holds the ERM in place (D) against the tactor housing (E) with the surface texture to be evaluated (F).

4.2.2 *Hierarchical Two-Alternative Forced Choice Paradigm*

The participant donned a thigh band with a marked location for consistent stimulus placement. The participant also donned a bandana around their eyes in order to eliminate visual bias and ensure their reliance on the sense of touch. The experimenter alternated twice between two housing choices, applying constant pressure during the 0.5s vibration time. Thus, for one decision instance, there are four total stimuli presented. The participant then indicated which of the two configurations elicited the stronger vibration. This procedure would continue at a given frequency for each comparison shown in the hierarchical structure in Figure 4.5, evaluating material, area, and pattern. After a trial at each frequency, the final comparison was between the configuration with the strongest vibrations at 70Hz and at 250Hz.

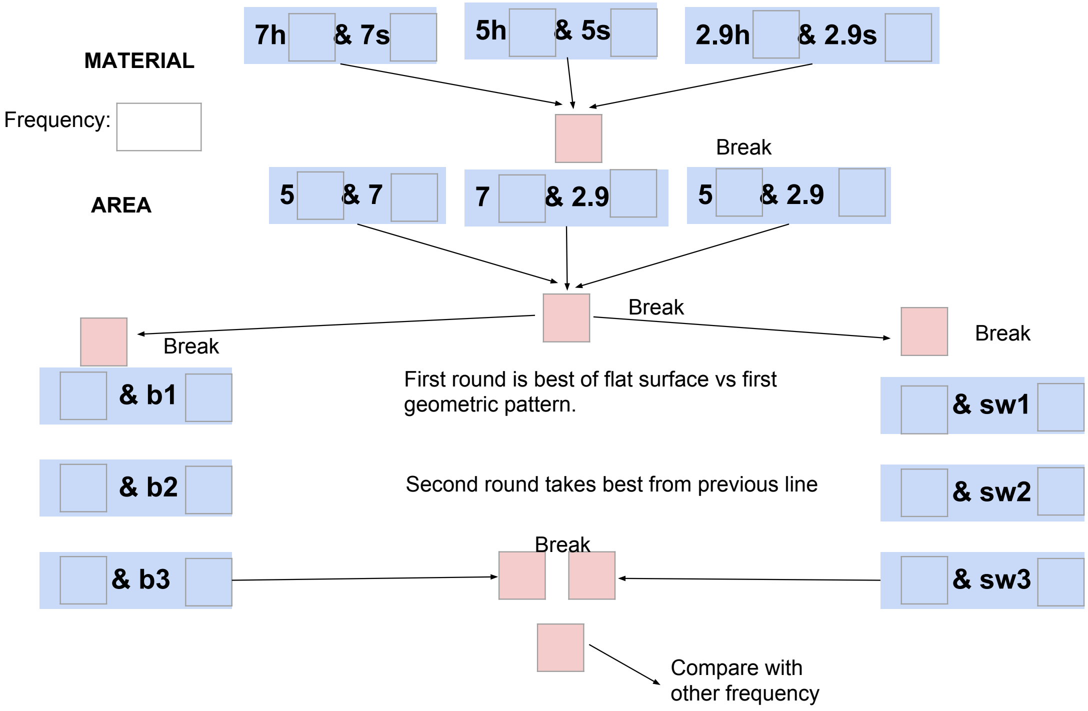


Figure 4.5. Hierarchical alternative two-forced choice testing paradigm template.

The alternative two forced choice test was chosen as the optimal testing procedure, as a systematic procedure in testing every combination against every other combination would yield over 1,000 test instances. If each comparison took half a second, the experiment would take approximately eight hours, by which point both experimenter and participant would be uninterested in continuing the experimental protocol. This structure is suitable as an initial evaluation of the parameters of interest, and subsequent studies may compare a fewer dimension of parameters in a more systematic and redundant way.

4.3 EXPERIMENTAL RESULTS

The hierarchical preference paradigm was evaluated on N=11 participants (aged 18-50, 5 female). Final participant preferences of tactor housing characteristics are shown in Figure 4.6.

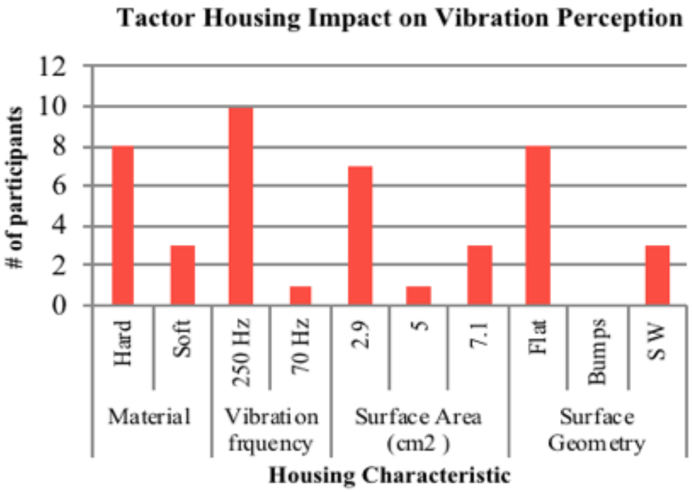


Figure 4.6. Final housing preferences, where each characteristic sums to the total number of participants responding.

The percentages refer to the percent of participants who selected a specific variation of a characteristic for their top choice. All but one of the participants found a 250 Hz vibration easiest to perceive. 72.7% of subjects preferred the rigid material. The small housings were preferred by

63.9% of the subjects. 72.7% identified the flat surface as conveying the strongest vibration. The distribution of motor housing characteristic choices was consistent among subjects and showed no correlation to differences in gender or age.

The interactions between any two housing properties can be combined in six ways: $\binom{4}{2}$. For instance, the relation between area and frequency shows that the single participant who preferred the 70Hz to the 250Hz vibration selected the 2.9cm^2 area. Of these interactions, the relation between material and geometry is of interest as it is the relation most divided by responses (Figure 4.7). Participants who preferred the square geometry only did so when the material was hard; when the material was soft, participants unanimously selected the flat surface.

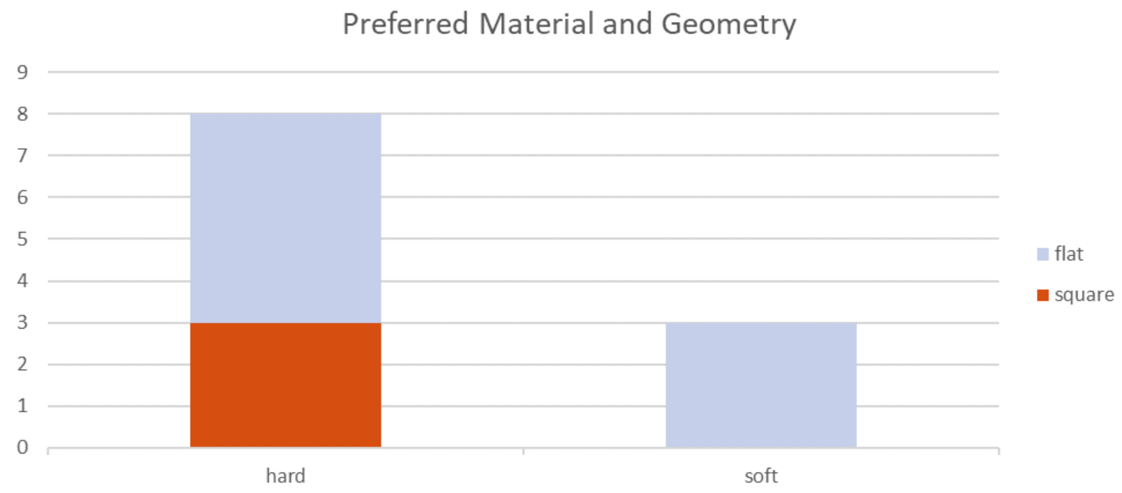


Figure 4.7. Housing preferences broken down by material and geometry. Participants preferred the square geometry only with the hard material.

4.4 Discussion

A clear outcome of this study was to confirm the preference for a 250Hz to 70Hz vibration. Less decisively, we show a preference toward a hard material over a more compliant one, a finding that warrants further study as it challenges intuition from literature on impedance matching for perception. Further, we show that the material preferences coincide with preferred geometry, though a causal relationship is yet undetermined. Understanding the principles by which these preferences occur may encourage optimal interface design to consider how the contact surface and material properties are interrelated.

Participant preferences of a specific vibration, material, surface area, and surface geometry indicate that these factors do influence perception of vibration. Identifying the elements necessary to develop a vibrotactile housing that elicits the strongest vibrotactile feedback has the potential to advance systems that already use vibration as a means of communicating with the user. This work justifies the need for further inquiry on how to best incorporate these findings into the construction of haptic feedback systems for lower limb prosthetics, such as the one developed in Chapter 2. These findings are also transferrable to upper-limb prostheses, as well as broader haptic and user interface applications.

Chapter 5. REFERRED SENSATION AFTER TARGETED REINNERVATION IN THE LOWER LIMB

Synthetic means of restoring sensory feedback are fundamentally limited. No matter how well a haptic device is designed, there still remains a chasm between what an intact neural sensation *ought* to feel like, and what an artificial sensation on the skin surface *actually* feels like. Some researchers choose to reinstate communication between brain and skin by implanting nerve stimulation devices to directly interface with the peripheral nervous system. Others surgically transfer undirected peripheral nerves so that they can reinnervate the skin. The latter process is called targeted reinnervation surgery, which is at the focus of this part of my research (Figure 5.1).

Targeted Reinnervation (Chapter 1.2) is a surgical approach that may restore sensation after limb loss, and has been made use of in sensory-integrated prostheses. Compared to transplantation, TR is less costly, requires less time in the hospital and in recovery, and can be applied to a wider amputee population; a further review of the comparative benefits of TR can be found in [50]. Though there have been studies to characterize and make use of sensory recovery in the upper limb after TR [13], and targeted reinnervation procedures have been developed for transfemoral and transtibial amputees [51][52], the lower limb's capacity for sensory reinnervation has remained unexplored.

We have developed a protocol for mapping the nature and extent of referred sensation in the lower limb, evaluated on a single participant that has undergone TR surgery. Of 25 sites surveyed, consistent referred sensation was identified in 4 areas, one of which appeared to be dependent on the pose of the phantom limb. We found this pattern of referral to be consistent in a follow-up visit several months later. Understanding the capability for referred sensation to the lower limb has enormous potential for the restoration of intuitive feeling.

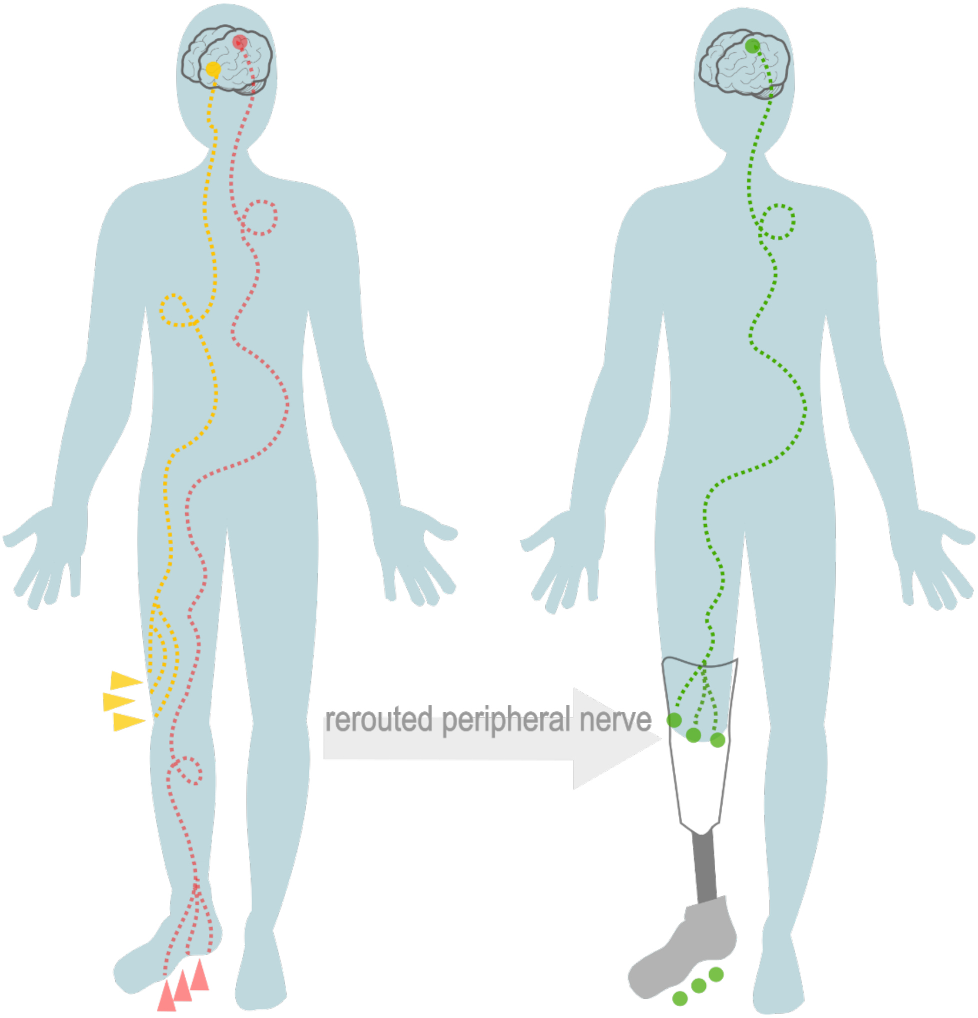


Figure 5.1. Targeted Reinnervation addresses the gap between what an intact neural sensation ought to feel like (red) and what an artificial source of feedback provides (yellow). By rerouting and stimulating peripheral nerves that formerly terminated in the amputated limb, a stimulus can feel as if it is physiologically consistent (green).

5.1 EXPERIMENTAL METHODS

Referred sensation at the residual limb was evaluated over the course of two visits. At the first visit, the residuum was mapped with a grid of points and stimulated with three different monofilaments, which are used to provide a constant pressure during a neurological examination of sensation. The user responded to the sensations using a graphical user interface (GUI) displayed on a laptop. For the second visit, a tactile re-evaluation of the residuum grid was performed with the medium monofilament.

5.1.1 *Participant Background*

The participant received a below-knee amputation in 1969 and has had 25 surgeries on the affected limb since. These include 3 total knee replacements, and a subsequent amputation above the knee in 2008. The most recent procedures have included end-to-end TR for managing pain. At the time of the study sessions, residual limb pain was rated as a 6, with no phantom limb pain reported.

5.1.2 *Graphical User Interface*

The GUI was displayed on a laptop (Figure 5.2) and displayed a frontal and dorsal view of the limb. The participant was also able to report qualities of the vibration, such as whether the sensation was buzzing, burning, painful, etc.

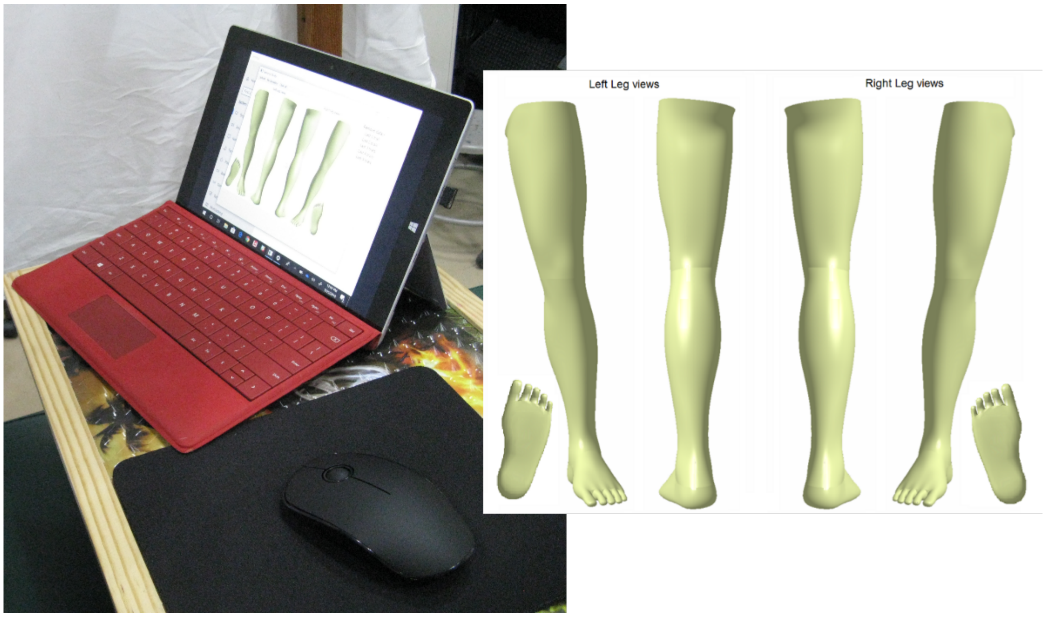


Figure 5.2. Image of the graphical user interface used for referral responses. The participant clicked on the site from which they felt the stimulus originate.

5.1.3 *Tactile Stimulation*

During the first visit, after informed consent, the participant was seated with the residual limb extending about 5cm over the edge of an examination table. Their view of the limb and experimenters was blocked with a curtain, and a computer displaying a graphical user interface for indicating sensation was positioned ergonomically to their right. The GUI was developed to prompt responses to a series of touches. The residual limb was marked with a grid of 25 stimulation locations (Figure 5.3). 225 total prompts were provided to the participant, 75 of which were sham touches designed to detect false positives. Each location was randomly stimulated with 6 real touches and 3 sham touches, using 3 Royland Semmes-Weinstein monofilaments of varying weight (2.05g, 5.50g, 15.00g).

The monofilament weights were selected to be unique to the participant. The participant was given a selection of monofilaments and asked to try them out on their residual limb to become familiar with the sensation. The 2.05g weight chosen was the lightest weight that was perceptible in at least half of the locations. The 15.00g weight chosen was the greatest weight that was not uncomfortable at any location on the residuum. The 5.50g weight was in the middle of the other two monofilaments.

During the second visit, the same grid was marked on the residual limb. The 25 marked sites were stimulated with the medium weight monofilament to locate the areas where there was no response, and to identify any painful locations.

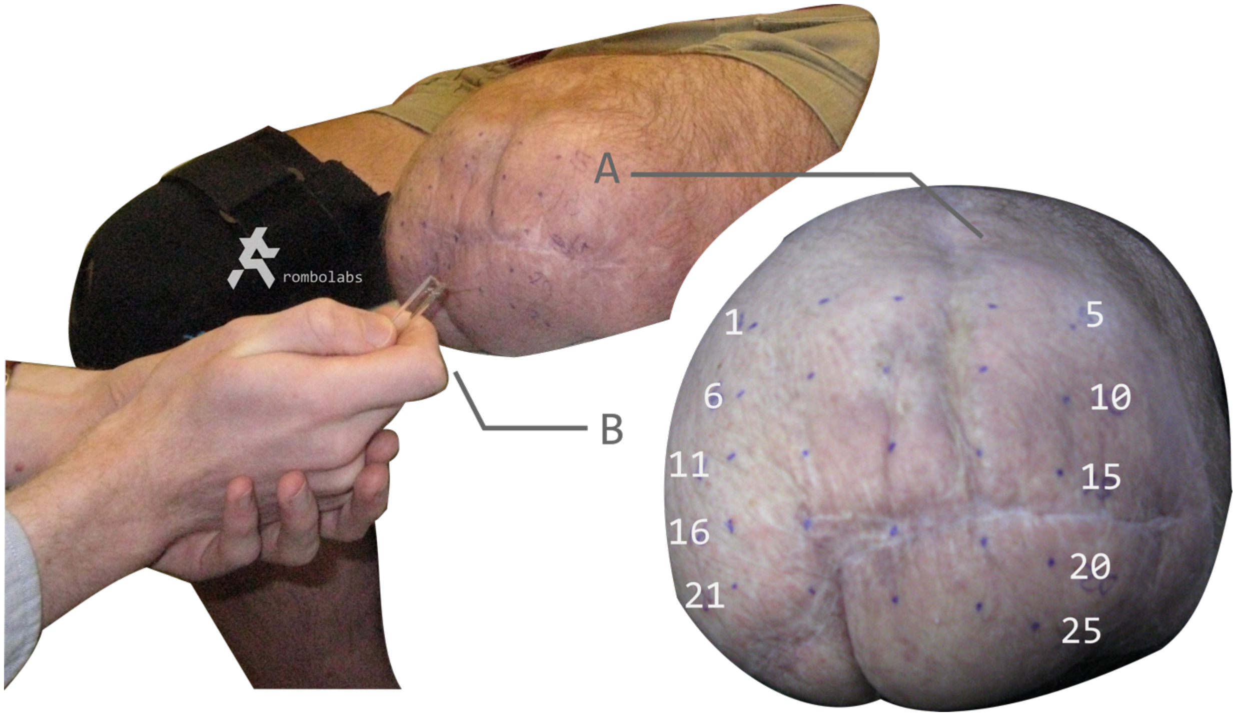


Figure 5.3. A view of the marked locations on the residual limb (A) stimulated by the monofilament (B).

5.2 EXPERIMENTAL RESULTS

Of 225 prompts, 77 prompts were responded to as being felt, 73 were not detected, and there were no false positives. The 77 detected touches and their subsequent GUI responses were used to develop the tactile mapping shown in Figure 5.4. Of these touches, 36.4% were prompted by filament 3, 27.2% by filament 2, and 36.4% by filament 1, where 1 is softest and 3 is hardest. The areas in gray are “dead zones”, where there was no response with any filament. Areas in black are responses that were not clustered consistently: the heuristic used to include a point in a colored cluster was “at least three responses, <20 pixels apart in the GUI”.

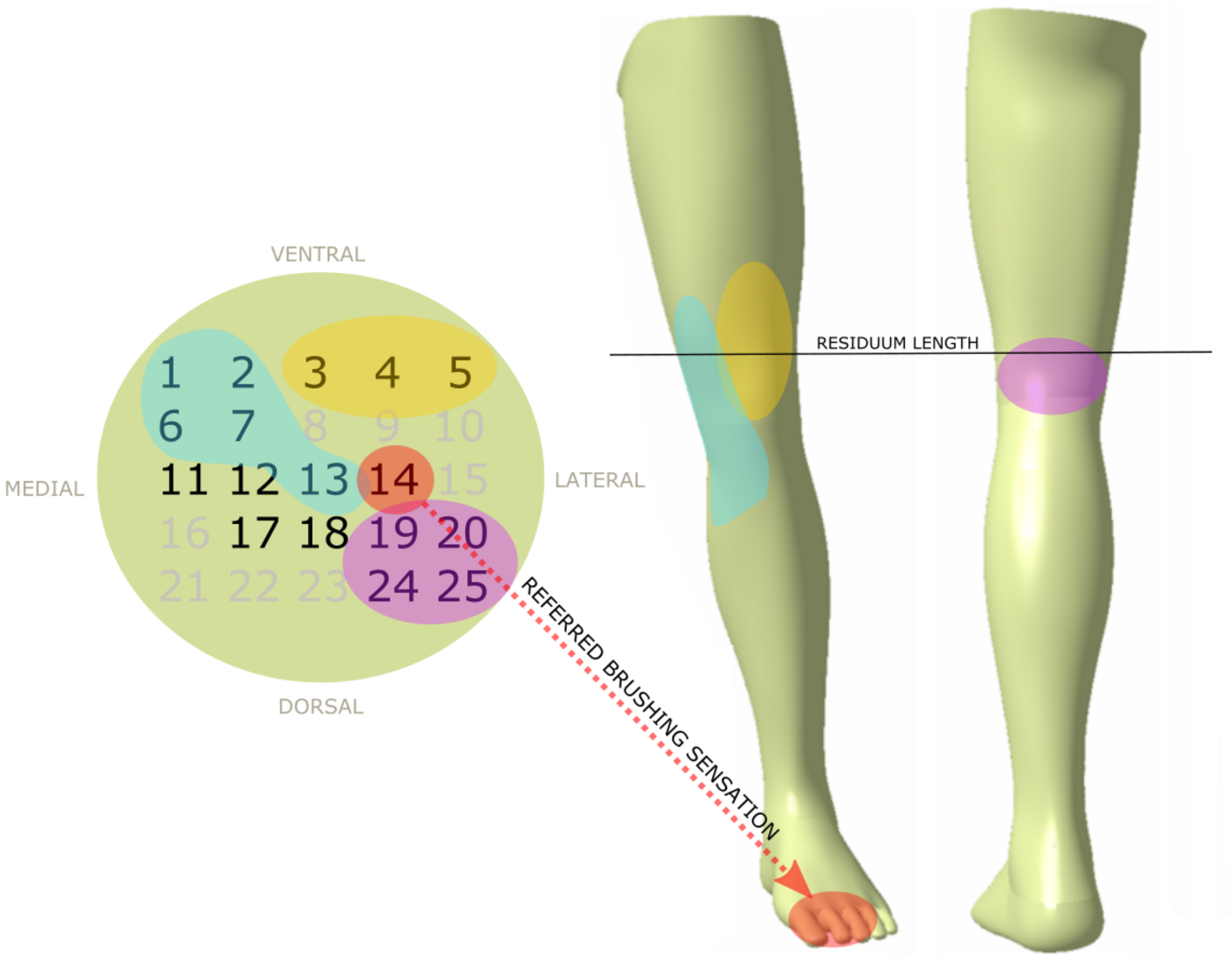


Figure 5.4 Tactile stimulation locations and map of referred sensations.

Site 14 in particular was isolated for exploration due to a report of a "brushing" referred sensation to the phantom foot. When the participant was asked whether they could manually elicit the referred sensation, they found that the referral was dependent on the pose of their phantom limb, which they discovered they could volitionally control by flexing muscles on the residual limb. Cutaneous stimulation when the phantom was flexed resulted in a referred sensation to the first 4 rays of the phantom limb. As the phantom was transitioned from dorsiflexed to plantarflexed, the referred sensation moved from the plantar surface of the big toe to diffuse across the next two toes. The participant had not been aware of this referred sensation prior.

At the second visit, site 14 was revisited and found to refer sensation to the phantom toe. However, stimulation of the sites horizontally adjacent (11-20) now also elicited referred sensation to the plantar surface of the phantom foot from heel to toe. The participant manually explored all sites on the residuum while contracting and relaxing the residuum, flexing and extending the phantom limb, and found that the nature of the referred sensation across these sites was “burning” but “not painful”. This finding indicates that the referred sensation was not consistent across time, potentially developing as a result of the patient’s extensive rehabilitation and visualization of their phantom limb after the first visit. Between the two visits, the participant had been training the flexion and extension of their phantom limb after discovering this ability at the first experimental session. The participant demonstrated their improved ability to control the flexion and extension of muscles at the thigh, which were reported as controlling the position of the phantom leg.

Commonly in upper-limb TR, the sites of muscle activation during phantom limb movement are superimposed on the sites of sensory referral. However, ad-hoc exploration of the outside of the leg with the monofilament did not yield referred sensation. The monofilament was applied across an area on the lateral aspect of the thigh about 4” from the distal end of the residual limb, proximally to about mid-thigh. This area was inconsistently sensitive, where sometimes a touch with a monofilament was felt, but a subsequent touch at the same location was not felt. This behavior ought to be explored further

5.3 DISCUSSION

This work demonstrates a viable method for the mapping of referred sensation in the lower limb after a tactile stimulus. This sensory map indicates apparent referral to sites distal to the point of amputation. For instance, the area spanning sites 1, 2, 6, 7 and 13, on the medial aspect of the residuum, induces sensation down the medial side of the leg to the calf of the phantom limb.

The participant was able to utilize their newfound volitional control over their phantom limb for rehabilitative benefit. In the time between the two experimental sessions, the participant worked with their clinical team to use active imagery of moving the phantom limb, coupled with flexion of muscles at the thigh. They report being able to move the phantom ankle “up and down” and move the phantom toe “only up, but not down.” There was a self-reported improvement in strength after several months of phantom limb exercise. This is notable, as it had been 4 years since the time of TR surgery, indicating a capacity for plasticity long after the surgical procedure.

Understanding the lower limb’s capacity for sensory reinnervation after TR surgery remains an important factor in the subsequent development of sensory-integrated prostheses. Executing this protocol longitudinally, working with a participant from the beginning of their recovery after TR surgery, through rehabilitation and full recovery, may provide additional insight into how the sensory maps evolve over time. As this work indicates, it can be empowering for study participants to discover their heretofore unknown capabilities and use their newfound understanding of their body for rehabilitative benefit.

Chapter 6. HAPTIC FEEDBACK AFTER TARGETED REINNERVATION IN THE LOWER LIMB

A map of referred sensation (Chapter 5) is the first step towards the implementation of a prosthesis that can provide feedback to the phantom limb that corresponds to the position of the prosthesis. Such a device would locally target the areas that induce a referral to the plantar surface of the phantom foot, and deliver a stimulus to those somatotopically-matched locations based on force sensor readings at the plantar surface of the prosthesis. Vibrotactile stimulation is a low-profile method of providing feedback to target reinnervated areas. It is non-invasive, can be easily integrated into a prosthetic socket, and has been implemented in the upper limb in TR recipients. However, the effect of vibration on referral in the lower limb has not been determined. Here, we describe the development of a vibrotactile device that is used to develop a mapping of referred sensation prompted by a haptic stimulus.

6.1 VIBROTACTILE DEVICE DEVELOPMENT

The vibrotactile device (Figure 6.1) uses the Adafruit Feather ESP8266 to elicit referred sensation with an eccentric rotating mass (ERM) tactor as a source of vibration. The tactor and force sensor complex cue a vibration when the force sensitive resistor detects a force above the 2.5g threshold. The experimenter presses one of two buttons corresponding to a 70Hz and 220Hz vibration stimulus. The device is battery-powered and does not record data for processing.

The two vibration frequencies used in this protocol were selected based on our prior work in characterizing optimal haptic interfaces. The use of a force threshold ensures that consistent pressure is applied throughout the experimental protocol.

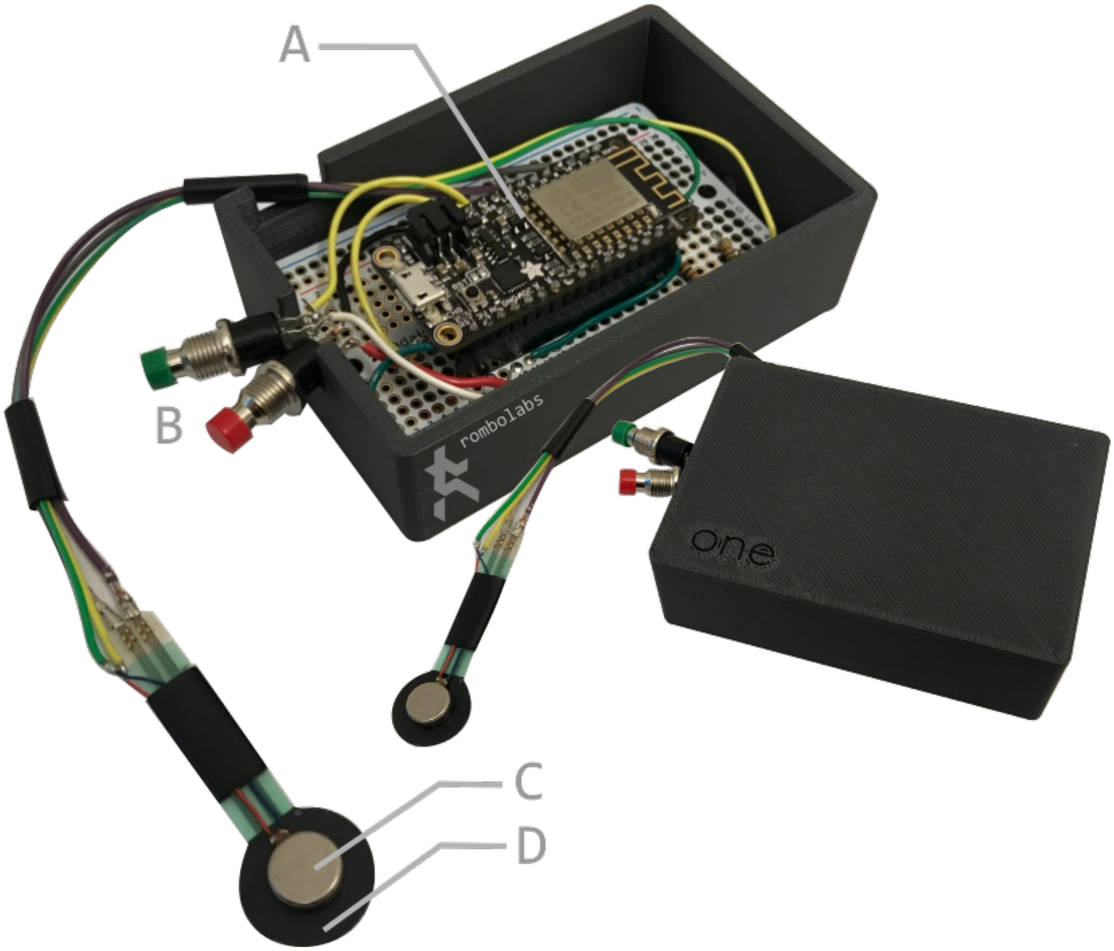


Figure 6.1. The vibrotactile device used to identify locations of sensory referral consists of an Adafruit Feather (A), pushbuttons for cueing vibration at 70Hz and 220Hz (B), an ERM tactor (C) and a force sensor (D).

6.2 EXPERIMENTAL METHODS

After informed consent, the participant was seated comfortably with the residual limb extending about 5cm over the edge of an examination table. Their view of the limb and experimenters was blocked with a curtain, and they faced a large monitor displaying a graphical user interface (GUI) for indicating sensation. The GUI was developed to prompt responses to a series of touches. The residual limb was marked with a grid of 25 stimulation locations (Figure 6.2).

Each of the 25 sites was stimulated with the vibrotactile device at the 2 frequencies, 3 times each; each site stimulus was presented in a triplet block, where one of the stimuli was a sham touch designed to detect false positives. Thus, 450 total prompts were provided to the participant, 150 of which were sham touches.

At each touch prompt, the participant was able to rotate the limb on the GUI using the arrow keys of a keyboard positioned ergonomically to their left, and used a mouse to click on locations where they felt the sensation originate. They were also able to report qualities of the vibration, such as whether the sensation was buzzing, burning, painful, etc.

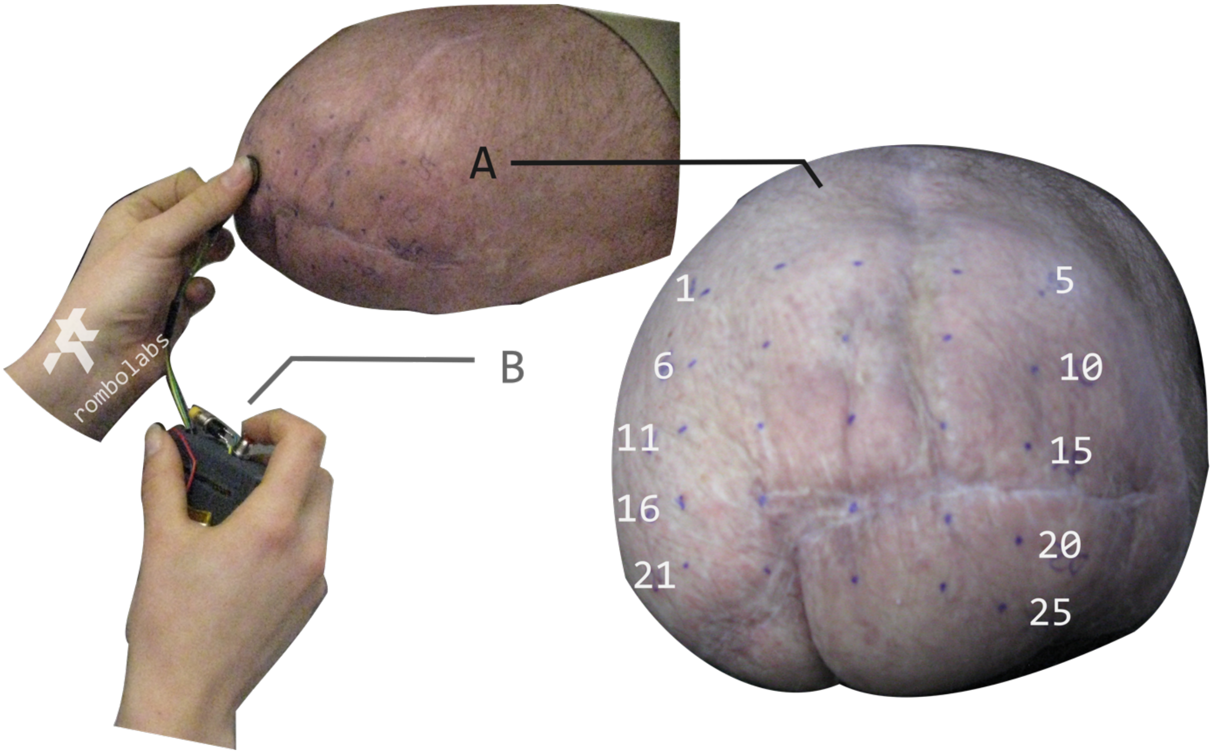


Figure 6.2. A view of the marked locations on the residual limb (A) stimulated by the vibrotactile device (B).

6.3 EXPERIMENTAL RESULTS

Of 450 prompts, 300 were real touches: 253 were responded to as being felt, 46 were not detected, and there were 7 false positives.

The false positives did not present systematically. That is, there was no apparent consistency on which points were liable to present a false positive, as locations of false positives were not repeated, and there was no influence of frequency, as 3 instances occurred following a 250Hz vibration, and 4 instances following a 70Hz vibration.

Of the undetected points, 52% occurred at 250Hz and 48% at 70Hz, indicating no relationship between frequency and perception of stimulus. Two clustered zones of low sensitivity occur: one at the dorsal-medial aspect, around points 21 and 22, and a second at the ventral-lateral aspect around points 5, 9 and 10. These zones of consistently undetected vibrotactile stimulus are consistent with the zones that do not respond to a tactile stimulus (gray zones shown in Figure 5.4).

The minimal threshold of detection was determined for each location. On the left of Figure 6.3 is a grid depicting the sites on the residual limb that were stimulated by the vibrotactor. Numbers in gray indicate sites for which there was no detection of stimulus. Sites in colored regions indicate consistent referred sensation, and those without color indicate highly variable response (greater than 20 pixels distance in any axis direction). On the right are regions indicated on the GUI as apparent origin of stimulus.

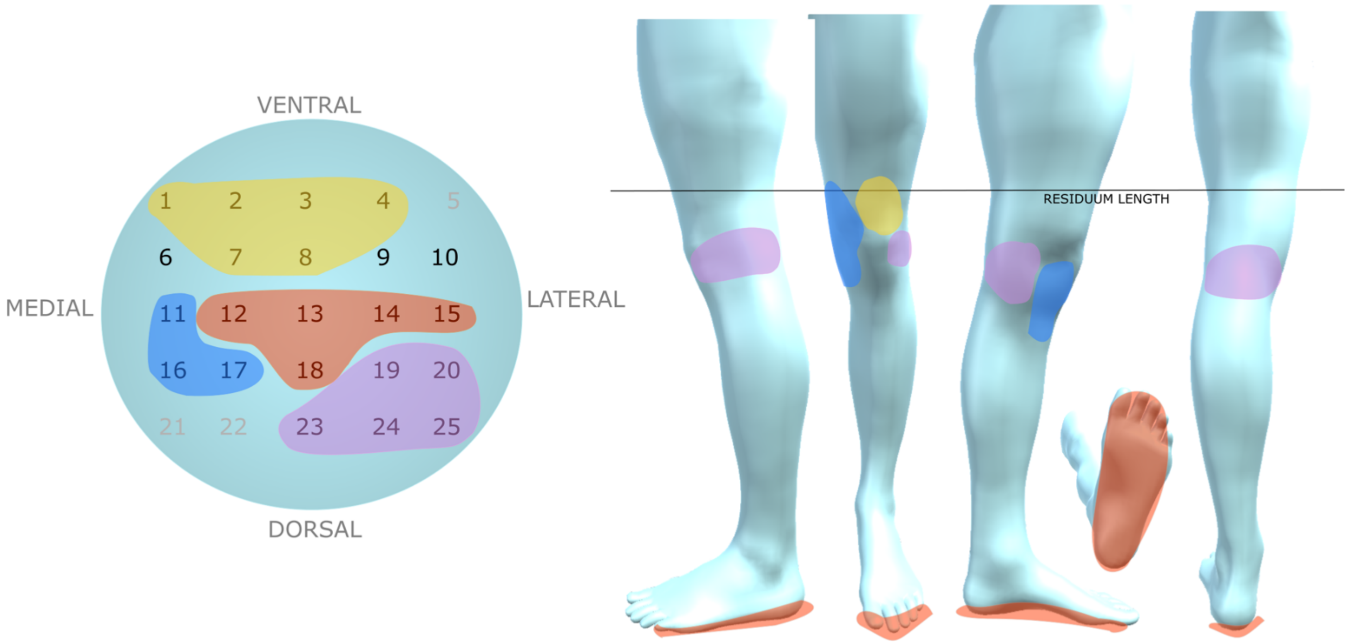


Figure 6.3 Vibrotactile stimulation locations and map of referred sensations.

This participant had previously demonstrated a referred sensation across sites 11-20 upon tactile stimulus. This sensation had been characterized as a “burning” but “not painful” and “not pins and needles” sensation that was felt at the plantar surface of the phantom foot from heel to toe. Directed vibrotactile stimulation to these sites induced a referred sensation to the same location on the foot, but the nature of the sensation was now less burning, “more pleasant”, and no longer extended to the toes. The sensation was induced with both the 70Hz and 220Hz frequencies, though the participant reported that the weaker 70Hz vibration was more comfortable.

Prior to this visit, the participant had been training the flexion and extension of their phantom limb after discovering this ability at the first experimental session. Commonly in upper-limb TR, the sites of muscle activation during phantom limb movement are superimposed on the sites of sensory referral. However, ad-hoc exploration of the outside of the leg with the vibrotactor did not yield referred sensation. The vibrotactor was moved across an area on the lateral aspect of the thigh about 4” from the distal end of the residual limb, proximally to about mid-thigh. Vibration strength did not appear to influence perception at this location.

6.4 DISCUSSION

These findings indicate that vibrotactile feedback can be used to successfully elicit referred sensation in the lower limb after TR surgery. When compared to the tactile mapping, there are fewer points that were scattered, or had inconsistent referral (sites in gray). Possible explanations are that haptic feedback is easier to detect than haptic feedback, or that the new GUI allowed the user to be more precise in indicating referral locations.

There was no difference in ability to detect a stimulus between the 70Hz and 250Hz case. The participant’s ability to detect a stimulus was dependent on the location of the stimulus, or whether it occurred in a zone of low-sensitivity, but was independent of the frequency of the stimulus applied. These preliminary findings are encouraging, as the loosening of constraints for optimal feedback frequency open greater design possibilities for user interfaces. Additionally, this allows for feedback devices to prioritize user comfort, rather than yielding to a trade-off between comfort and perception. The participant indicated during the experiment that the lower frequency stimulus felt more comfortable. Future work in assessing the optimal skin-to-motor interface for recipients of TR surgery would elucidate whether these findings indicate that the TR population has unique sensory requirements when compared to control cases.

It was found that the vibrotactile stimulus presented was more noticeable than the tactile stimuli. Perception of the haptic stimulus occurred 84.3% of the time it was presented. In contrast, a tactile stimulus was only perceived 51.3% of the time it was presented. The low perception rate of tactile stimuli cannot be attributed to the varying monofilament stiffnesses. For monofilaments 1,2, and 3, the perception rate was 53%, 46%, and 55% respectively. This finding confirms that vibrotactile feedback is a suitable paradigm for providing sensation to the user. Subsequent work will evaluate in what ways feedback can be presented appropriately in order to assist the user in dynamic task performance.

Referral to the phantom foot was found in the same location when using both the monofilament and vibrotactor. This confirms intuitions about vibration and tactile stimuli targeting the same area of skin and the same location of neuroreceptors. However, the two different stimuli yielded different qualities of sensation. With a tactile stimulus, the sensation was tightness and diffuse burning, whereas with vibrotactile stimulus, it was only a light burning. A possible explanation is the recruitment of different neuroreceptors with vibration versus touch, and this difference being responsible for two different sensations despite the stimuli being applied in the same location. Additionally, with the vibrotactile stimulus the sensation no longer extended to the toes. This may be because there was a smaller force applied, and the nerves responsible for sensation at the toes were embedded more deeply in the tissue after the surgery. A follow-up study to measure force applied during a referred sensation with a vibrotactile stimulus may expound upon this claim.

There was consistency between tactile and vibrotactile mapping. Referral to the back of the leg was induced from sites 19, 20, 24 and 25 in the tactile case, and 19, 20, 23, 24, and 25 in the vibrotactile case. Sites that referred sensation to the ventral aspect of the leg increased in number and shifted medially. Sites that referred sensation to the medial aspect of the leg shifted dorsally. These two shifts may be explained by the increased number of sites that referred sensation to the plantar surface of the foot; as this area increased, it may have caused a rearrangement in mapping.

The characterization of sensory referral using a vibrotactile stimulus is a critical step towards the development of a custom sensory-integrated prosthesis. If this participant were mobile, we would be able to develop a custom prosthetic socket with embedded vibrotactors at locations corresponding to the heel or the toe of the phantom limb. Vibration would be cued by readings at force sensors on the plantar surface of the prosthetic foot, thereby closing the sensory loop. However, the development of an experimental prosthesis is not the unitary successful outcome of such a study, as these findings of referred sensation and volitional control over a phantom limb have been largely beneficial to this participant's rehabilitation and pain management.

The protocol described above is deployable to any research center with connection to interested recipients of TR surgery in the upper or lower limb. Subsequent investigation would show whether the use of a sensory feedback prosthesis would increase usefulness of the device, promote frequent use, improve subjective metrics of quality of life, or increase performance in dynamic tasks such as level-ground walking, stability, or stair navigation.

Chapter 7. CONCLUDING THOUGHTS AND FUTURE QUESTIONS

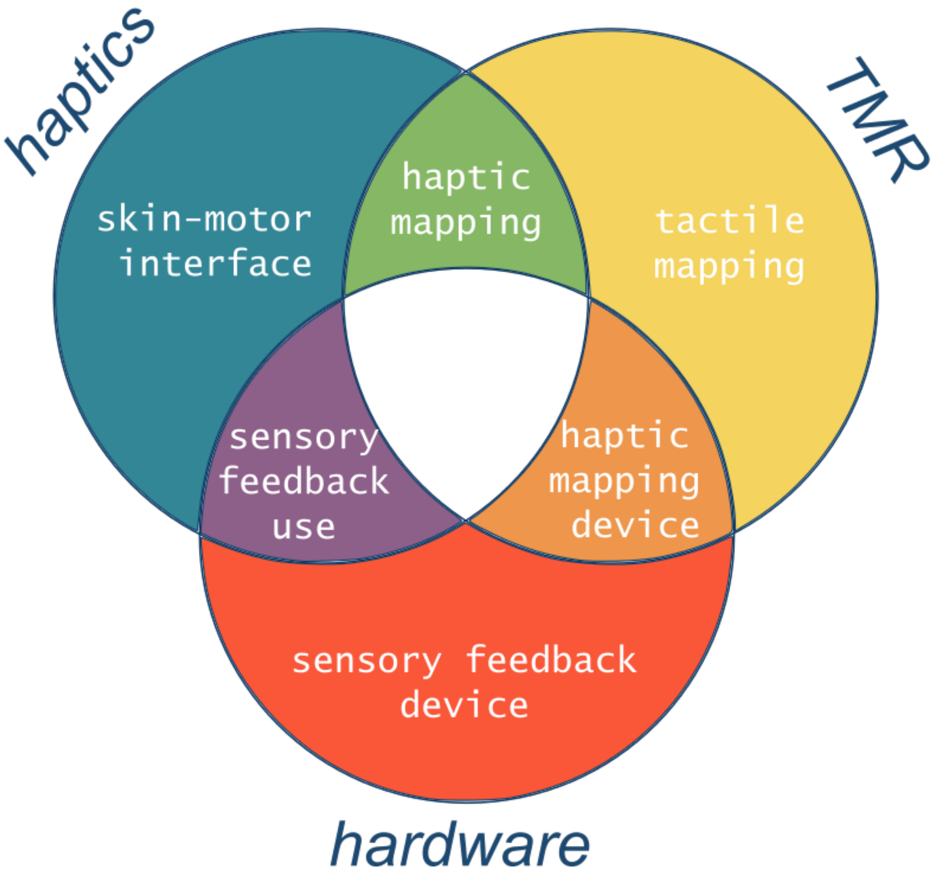


Figure 7.1 A concluding view on the intersecting components of this thesis.

In this work, we have demonstrated the implementation of a prosthetic sensory feedback device for stair descent, identified optimal characteristics for a lower limb haptic feedback device, and made progress toward the development of a sensory-integrated prosthesis for TMR recipients. Figure 7.1 provides an orientation for what has been accomplished. The three intersecting areas of haptics, hardware development, and TMR span the space of how sensory feedback can be integrated in the development of lower limb prostheses. There is an argument to be made for the importance of sensory feedback in lower limb prosthesis development. This work provides an oblique sort of support for that argument: here, we have shown that the application of sensory feedback in one specific task improves performance in that singular task.

7.1 COGNITIVE LOAD

Questions that demand answers span all the components of this project. There is more work to be done in every one of these spaces and further directions to explore. There are questions that permeate throughout the work: for instance, what is the effect of vibrotactile feedback on cognitive load? To combat cognitive load, the nervous system is particularly adept at extracting sensory information that is task relevant and ignoring all other unimportant information. In particular, when an action is felt to be self-generated, we predict the sensory consequences of the action and subsequently attenuate those components of the sensory space [53]. An example: trying to tickle yourself. The functional purpose of this sensory attenuation is thought to be for improving perceptual performance in detecting external events [54], as the cancellation of self-generated sensory outcomes frees up cognitive space for responding to the unpredictable. Hence, cognitive load from the use of vibrotactile feedback is likely dependent on whether the feedback is felt to be self-generated.

Future work will also evaluate the importance of location matching on the uptake of useful sensory data and its effect on cognitive load. This can be made evident by comparing within-participant performance of TR recipients executing a dynamic task, such as stair descent, when the feedback is provided to the thigh versus when the feedback is provided to the reinnervated area corresponding to the plantar foot surface.

The single-use cases we evaluated above do not indicate whether or not the feedback device was subsumed into what is under endogenous control. Instead, ascertaining cognitive load will require a longitudinal study where “self-generation” or *ownership* over the device is evaluated.

7.2 OWNERSHIP

Body ownership is a promising avenue of study in its potential to increase prosthesis use and retention. Future work will address whether a user of a sensory-integrated prosthesis will extend full ownership over a prosthetic leg when it is providing them feedback, and how ownership depends on feedback being indistinguishable from the physiological. As suggested above, it may not be essential for the feedback to be of a matched modality to the original sense. Anecdotally, we incorporate outside objects with non-native modalities into our *body schema* all the time: whenever I am not wearing my watch, I still find myself glancing at my left wrist as if it could tell me whether I'll be late for my next meeting. Body schema is a fussy term that is used here lackadaisically. First defined by Sir Henry Head [55], it consists of "the impressions produced by incoming sensory impulses in such a way that the final sensation of position, or of locality, rises into consciousness charged with a relation to something that has happened before". Modern interpretations use the term to refer to an unconscious internal model constantly updated with sensory, proprioceptive, spatial, and motor information on the behavior of the body. To incorporate something into the body schema is to make use of that object's reciprocal effects on the spatial representation of the body and its supramodal influence on the senses.

Gait is an excellent medium for these studies, as it is cyclical in a way that discrete upper limb movements are not. Perturbing sensory feedback parameters in real time after a period of habituation may indicate to what degree the body is using the feedback modality in a useful way. For instance, once a device is well incorporated into the body schema, performance at executing a dynamic gait task will be static. If the helpful feedback that device provides is suddenly removed, we would expect to see decreased performance, indicating the user's reliance on the device.

7.3 LONG-TERM USE

Questions of ownership and cognitive load, as well as prosthesis retention and improvements to quality of life, require a longitudinal study to answer. On a long timescale, many possible relationships between user and device can form. Colleagues have inquired whether a user will habituate to a source of vibrotactile feedback and no longer use it effectively. Though this outcome is possible, I refer these and other cynics to their cell phone habit and how attuned they are to its vibration. When a sufficiently important event is on the other side of the stimulus, such as an email or a successful stair step, sensitivity will likely remain appropriately high. The dynamics of the learning rate of skillfully using such a system ought to be studied further to confirm this intuition. Of course, successful use over the long term depends on whether the feedback modality has been tuned appropriately: not too strong so as to induce peripheral nervous system damage [56], and not too slight to prevent reliable discrimination and use.

Furthermore, the nervous system's plasticity and interdependence on musculoskeletal function, as demonstrated by our TR patient's capacity for expanding their sensory referral map after strength training, is deserving of further investigation. Studies on long-term cortical plasticity after targeted reinnervation have found that both motor cortical maps [57] and sensory cortical maps [58] are restored to close to 'normal' baseline conditions. The effect of rehabilitation on cortical or referral plasticity is still unknown. After further study on the long-term outcomes of strength training after TR surgery, developing therapeutic guidelines and clinical best practices for increasing sensory referral would serve to make TR a more common and readily accepted procedure.

7.4 ET CETERA

Broadly, this work contributes to the conversation of how a device attached to the body can be made most useful. Furthermore, one ought to ask, if something is useful, how much ownership does the user exert over it? And if there is a lot of ownership felt, can this device's function be as good as a physiological limb? Can it be better? Can a system be designed such that it provides more sensory information than is physically possible, allowing the user to explore parts of the world they wouldn't have exposure to physiologically? Could they feel magnetic attraction like birds do, or identify ultraviolet signatures like butterflies? The use of sensory feedback in the lower limb is one of many possible approaches to answering the next frontier of these cyberphysical and science-fictional questions. These are the incipient efforts to tunnel into the sensorimotor mountain. Similar aims out of neuroscience, applied medicine, haptics, robotics, and human-machine interaction will eventually converge in this space, discovering and applying the principles of sensory feedback to the next generation of interactive tools.

I have avoided many complex topics in my interpretation of this work. That is not because these topics are unimportant or uninteresting. But, however we ultimately decide to move forward in understanding and applying how the body is molded by what it can feel, I will leave the main question I want to raise here unanswered.

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