Conveying the Configuration of a Virtual Human Hand Using Vibrotactile Feedback

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ABSTRACT

Upper-limb prostheses users lack proprioception of their artificial arm, and rely heavily on vision to understand its configuration. With the goal of reducing the amount of energy expended on visual cues during upper-limb prosthesis use, this study investigates whether haptic feedback can relay the configuration of a virtual hand in the absence of sight. Two mappings from waistbelt-mounted tactor vibration patterns to hand configuration are explored: (1) Synergy-based hand motions derived from the results of a principal component analysis run on an aggregate of hand motions and (2) Decoupled hand motions, which include experimenter-selected motions such as finger grasp and finger spread. Results show that users can identify complex hand configurations with vibrotactile feedback patterns based on both the Synergies and Decoupled methods, although 30-45 seconds are required to achieve this task. Also, findings demonstrate that users are likely to memorize correspondence between an overall feeling of the tactor pattern to a hand configuration rather than constructing the hand configuration by isolating and considering each tactor individually. Last, results indicate that hand configuration is most accurately conveyed by maximizing information along a synergy-based space.

KEYWORDS: Haptic Feedback, Vibrotactile Feedback, Hand Synergies, Prosthetics, Sensory Substitution

INDEX TERMS: H.5.2 [Information Interfaces and Presentation]: User Interfaces-Haptics I/O; H.5.2 [Information Interfaces and Presentation]: User Interfaces-Input Devices and Strategies; H.1.2 [Models And Principles] User/Machine Systems-Human Information Processing; I.5.2 [Pattern Recognition]: Design Methodology – Classifier Design and Evaluation

1 INTRODUCTION

A great deal of visual attention is required to control current commercially available prostheses, in part because sight is heavily taxed to obtain haptic information. A poll of upper-limb prosthesis users indicates that they desire for artificial limbs to require "less visual attention to perform certain functions" [1]. Relaying proprioceptive cues through artificial haptic sensations is a way by which the cognitive effort expended on sight can be reduced [2]. Here, we investigate methods to present complex position and motion information in a compact and intuitive way, with the goal of minimizing cognitive loading of the visual channel during upper-limb prosthesis use.

Human hand motion can be decomposed into a linear sum of simplified hand motions [3,4]. We investigate whether a person can combine information about simplified hand motions to identify an overall hand configuration. In order to convey simplified hand motions to a user, we employ sensory substitution, which in this study involves vibrating elements to indicate the state of simplified hand motions. We test two different simplified hand motion paradigms and investigate their effectiveness in relaying a virtual hand's overall configuration (Figure 1). The first method, called *Synergies*, is based on principal component analysis, where an *n*-degree-of-freedom (DOF) system is decomposed and represented by *n* principal motions that are orthogonal to one another. In the second method, called *Decoupled*, discrete motions are selected by the experimenter based on pilot testing and anecdotal observations.

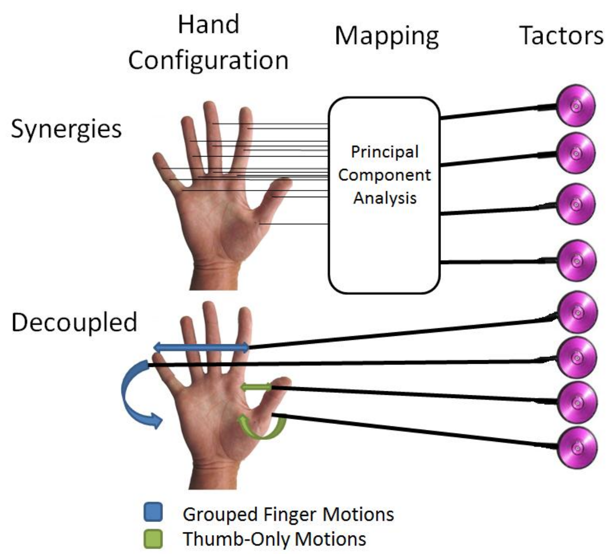

Figure 1: Methods for mapping hand motion to a vibrotactile array. **A.** 20 degrees of freedom are filtered to the four largest principal components from a synergies-based analysis, and then mapped to the C2-tactor array. **B.** Four decoupled hand motions are mapped one-to-one onto the C2-tactor array. Blue arrows mark the motions that involve all fingers aside from the thumb (finger spread and grasp), while the green arrows denote the thumb-only motions.

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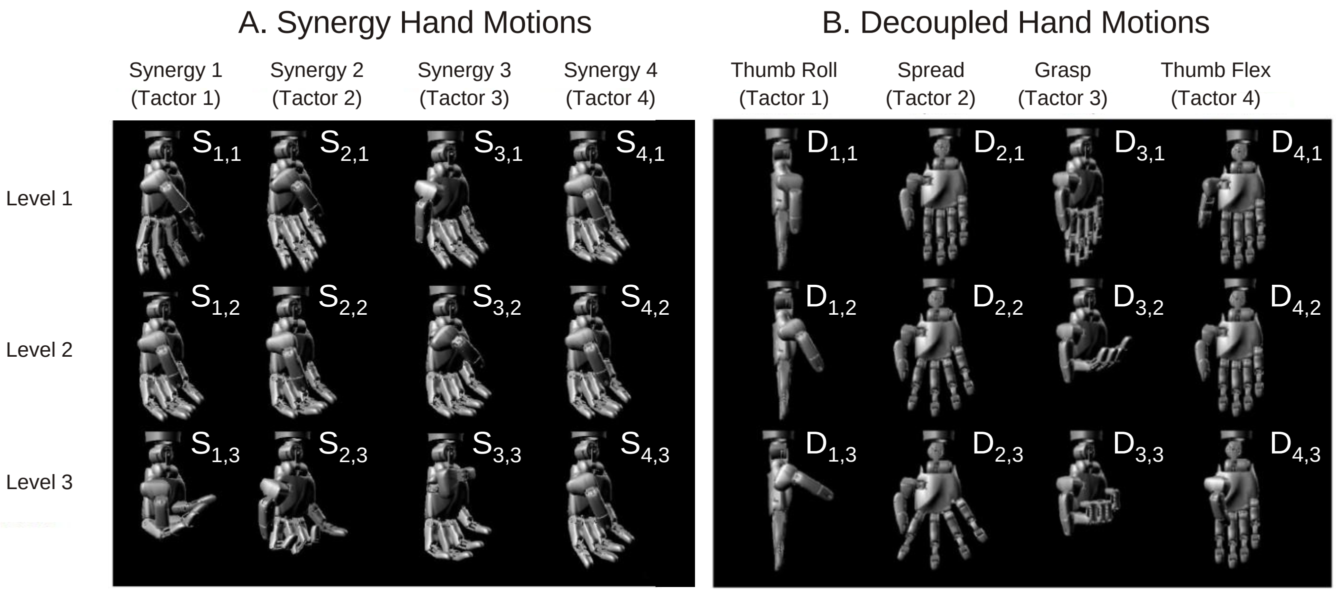

Figure 2: Levels of a motion for both the Synergies and Decoupled methods. **A.** Synergies: as the synergies increase in level, the following changes occur. Synergy 1: grasping of the fingers by flexing the metacarpal joints; adduction of the fingers. Synergy 2: grasping of the fingers by bending the proximal joints; extension of the thumb at the metacarpal joint. Synergy 3: flexion of the thumb at the metacarpal and carpometacarpal joints. Synergy 4: scissoring of the fingers. **B.** Decoupled: as the hand motions increase in level, the following changes occur. Thumb roll: abduction of the thumb away from the plane of the palm. Spread: abduction of the fingers away from each other. Grasp: grasping of the fingers by flexing the metacarpal and proximal joints. Thumb flex: flexion of the thumb at the metacarpal and carpometacarpal joints.

We show the effectiveness of both methods for conveying hand configuration. Even though the primary motivation of this work is to test a novel sensory feedback method for minimizing the visual burden during upper-limb prosthesis use, the sensory substitution methods examined here extend to other research areas including rehabilitation and providing novel methods for heightening haptic perception capabilities to those with compromised sensing.

2 Background

2.1 Methods to Relay Hand Proprioception

Auditory, visual, and haptic sensory modalities have all been tested for relaying hand position and motion information to users of upper-limb prostheses [2,5-7]. Here, the goal is to convey hand configuration artificially, while minimizing interference in one's ability to perform activities of daily living. Thus, we employ the haptic channel so that the functionality of the auditory and visual modalities is not directly affected.

Haptic methods for artificially conveying limb configuration have been tested both invasively [8,9] and non-invasively [2,6,7]. Given that invasive stimulation methods are not currently feasible for naturally and safely relaying proprioception, we investigate non-invasive haptic stimulation methods. When conveying hand position and motion artificially through non-invasive means, design considerations include stimulation device, number of stimulation elements, and stimulation location on the body.

Electrocutaneous, vibrotactile, and skin stretch stimulation are all non-invasive methods that have been tested for relaying position information to upper-limb prosthesis users. One study showed that relaying shoulder position information using electrocutaneous feedback improved performance in a shoulder-positioning task over no sensory cues, but not as well as visual feedback [6]. Vibratory feedback has also been tested in a task in which proprioceptive information was artificially relayed using vibrotactile elements. The vibratory cues were deemed subjectively important for conveying position and motion information in a grasping task, but did not improve performance over only sight [2]. Skin stretch feedback is a more recently proposed method for artificially conveying proprioception. During a sighted targeting task, artificial skin stretch cues resulted in performance superior to vibrotactile feedback, which was superior to no haptic feedback [7].

For this research, we are interested in a system that is small, portable, and can stimulate using numerous haptic elements. Given that the skin stretch device is not currently available in a compact, user-friendly package and it is not known whether skin stretch feedback is effective when multiple devices are simultaneously activated, we chose to build a system using vibrotactile feedback.

2.2 Vibrotactile Feedback

Vibrotactile feedback is a common method for haptically relaying information. A research overview of wearable vibration displays is provided in [10]. Conveying hand configuration to upper-extremity prosthesis users with vibratory stimulation is challenging for reasons including: (1) identifying an effective stimulation location on the body that still permits performance of activities of daily living, and (2) developing a mapping from hand configuration to vibrotactile stimulation that successfully conveys large amounts of information in a simplified manner.

Prior research investigated the effectiveness of various locations on the body for relaying vibrotactile cues, including the fingertip, toe, forearm, neck, wrist, and torso [11-13]. To minimize interference during activities of daily living, the torso may be an appropriate stimulation location. Vibratory feedback to the torso yielded superior identification results than the forearm in one study [12], and in another study vibratory cues at the finger, forearm, and torso all gave comparable performance [13]. For both of these studies, feedback was applied to the lower back.

Many research groups have used the C2 tactor (Engineering

Figure 3: Belt with four C2 tactors, and placement of vibrotactile belt on user.

Acoustics, Inc., Casselberry, FL), a commercially available vibrotactile element, for relaying artificial vibratory cues, e.g., [7,14-15]. Advantages of the C2 tactor include that it is commercially readily available, easy to use, produces strong localized vibrations, resonates at 250 Hz (the peak detection frequency of Pacinian corpuscles), and has a fast response time.

It is possible to actuate the C2 tactor using a variety of methods. For example, the amplitude and frequency of actuation can be modulated. Chatterjee et al. [16] showed that varying envelope frequency is an effective method for conveying information to prosthesis users. This activation method changes a higher-level envelope frequency, such that the amount of time the tactor vibrates at the desired frequency of 250 Hz is varied. Based on these findings, we chose to actuate the tactors by varying envelope frequency.

2.3 Simplification of Hand Motion Information

The human hand has more than 20 DOF. Even though a large number of possible hand configurations exist, the human hand can be simplified and described by "synergies", or an orthogonal set of hand motions obtained by performing a principal component analysis (PCA) on a set of natural hand motions [3,4]. Differing types of manipulation tasks (e.g., grasp vs. pinch) yield different synergistic sets [17]. A study that spans a large range of natural hand motions, including grasping, pinching, and free exploration, was used to derive the synergistic set we employed [3]. 85% of the variance in hand movements were accounted for by the first four synergies.

Mosier et al. [18] have shown that subjects can map complex motions of the hand into a two-dimensional space through control of a cursor on a screen. They showed that subjects were able to reduce the variability in hand motions and cursor movement over time, indicating that subjects were able to learn the mapping well.

Based on these studies, we propose that it is possible to reduce sensory information about complex hand configuration to only a few dimensions. While synergies represent the most efficient way to maximize hand motion variance, other sets of orthogonal and non-orthogonal hand movements exist that may have advantages over synergies, such as ease of learning.

3 System Design

A haptic system was designed for relaying hand configuration using sensory substitution (Figure 1). Visual feedback is used for training purposes (Figure 2), and four vibrotactile tactors convey simplified hand motions (Figure 3). Two mappings from vibratory stimulation pattern to hand configuration are tested: Synergies and Decoupled.

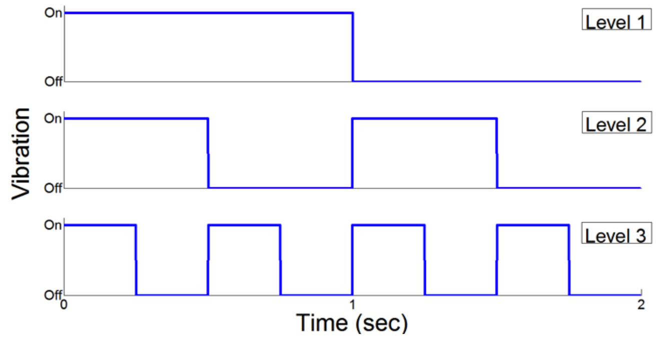

Figure 4: Three envelope frequencies sent to the C2 tactors. The 250 Hz vibration produced by the C2 tactor is enveloped in one of the following frequencies corresponding to discretized levels of a particular hand motion. From top to bottom: level 1: 0.5 Hz, level 2: 1.0 Hz, level 3: 2.0 Hz.

3.1 Simplified Hand Motions

3.1.1 Synergies Method

This method is based on the synergies research discussed in Section 2.3, and is useful because it maximizes hand motion variance. The first four synergistic movements from [3] are used, and describe 85% of the variance in hand movements. They are shown in Figure 2A, broken down into three snapshots over the course of each synergistic movement.

3.1.2 Decoupled Method

This method was developed with the motivation of making it easier to learn hand movements by using a set of simple, intuitive hand movements. For example, most tested synergistic movements (Section 3.1.1) have multiple fingers moving simultaneously, many times co-representing thumb motion along with other finger motions. As a result, in order to reconstruct thumb motion, a user would have to combine several synergies containing thumb *and* non-thumb movements, which may be confusing. The Decoupled method, however, separates broad categories of hand movement, including thumb versus non-thumb movements, into separate hand motions. Although the Decoupled method has the advantage of simplicity, it cannot, by definition, span the same amount of hand variance as the synergistic movements. The four motions selected, based on pilot testing and anecdotal commentary, are finger grasp, finger spread, thumb flex, and thumb roll. Figure 2B shows three snapshots over the course of each simplified hand motion.

3.2 Vibrotactile Waist Belt

Proprioceptive information about a virtual hand (Figure 2) is artificially relayed using C2 tactors that stimulate the torso (Figure 3). Pilot testing showed the abdomen to be more sensitive to vibrations than the lower back, leading to the design choice to place tactors along the abdomen. The tactors were equally spaced, with placement on the left side (Tactor 1), left abdomen (Tactor 2), right abdomen (Tactor 3), and right side (Tactor 4). The tactors were driven with a 250 Hz square wave at an amplitude of 10 V. Displacement of the end-effector is on the order of millimeters. The signal sent to each tactor was 30 ms out of phase with the next tactor, to aid in tactor discrimination.

3.3 Mapping Hand Configuration to Tactor Vibrations

Each simplified hand motion, which defines a continuous range of motion, was discretized into three levels that describe the degree

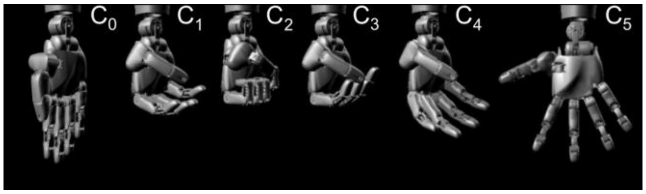

Figure 5: The initial reference position C_0 and the five tested hand configurations - C_1 cup grasp, C_2 clenched fist, C_3 finger/thumb pinch, C_4 ball grasp, C_5 wave.

to which the hand has moved along a particular motion (Figure 2). The level is conveyed to the user by varying the envelope frequency (Figure 4) of the tactor corresponding to the hand motion. Envelope frequencies are delivered in a carrier frequency of 250 Hz at 0.5, 1.0, and 2.0 Hz for Levels 1, 2, and 3, respectively.

The following syntax is used in this paper. For the simplified hand motions, 'S' stands for Synergies and 'D' stands for Decoupled. The first subscript (1, 2, 3, or 4) indicates the tactor being actuated on the vibrotactile waist belt, which in turn, corresponds to one of the four Synergies or Decoupled hand motions. The second subscript describes the Level (1, 2, or 3) delivered to the subject using envelope frequencies. Thus, $S_{2,3}$ represents the 3rd level of the 2nd tactor, and $D_{1,1}$ represents the 1st level of the 1st tactor.

In this study, subjects are instructed to identify five unique hand configurations, referred to as C_1-C_5 (Figure 5), using the tactor patterns relayed by the Synergies mapping and Decoupled mapping, as specified in Table I. It is important to note that the tactor patterns used for the Synergies and Decoupled methods are different, and that the difference between two Decoupled tactor patterns is less variable than the difference between two Synergy tactor patterns. This difference in variability affects one's ability to discriminate hand configurations, as discussed in Sections 6.1 and 6.2.

3.4 Visual Feedback and System Integration

To visualize hand motions, we used open-source software called Musculoskeletal Modeling Software (MSMS), developed at the University of Southern California [19]. This software simulates movement of prosthetic limbs through an intuitive user interface and can construct any hand configuration. It readily interfaces with MATLAB, which was used to supply MSMS with joint angles for the 27-degree-of-freedom virtual hand. The MATLAB program sent a set of joint angles to MSMS, and in concert with this command, sent a set of tactor levels for the corresponding hand motion types to an Arduino Uno board. The Arduino then interpreted the command and constructed the appropriate signal to actuate each tactor.

4 Experimental Design

4.1 Subjects

Approval from the Johns Hopkins University Institutional Review Board was obtained to collect data from human participants. Six female and eight male subjects participated with an average age of 24. Subjects were healthy and reported no neurological illnesses.

4.2 Procedures

Each subject tested one method (Synergies or Decoupled) per day over two days. Half of the subjects (three females, four males) used the Decoupled method on Day 1 and Synergies on Day 2, and the other half used the Synergies method on Day 1 and Decoupled on Day 2. Subjects removed any bulky clothing, since the tactors were placed over the shirt. Then the positioning of the tactors was adjusted around the torso until a clear signal was perceived from each tactor. Subjects trained for 30 minutes with visual and vibrotactile feedback on all individual tactors and each of the five final hand configurations, C_1-C_5 (Figure 5). The ability of subjects to discriminate among the five hand configurations using only vibrotactile feedback was measured.

Table I. Tactor patterns for each hand configuration for both the Synergies and Decoupled methods.

Hand Configuration	Synergies*	Decoupled*
C_1	$S_{1,2}$ $S_{2,2}$ $S_{3,1}$ $S_{4,3}$	$D_{1,3}$ $D_{2,1}$ $D_{3,2}$ $D_{4,2}$
C_2	$S_{1,3}$ $S_{2,3}$ $S_{3,3}$ $S_{4,3}$	$D_{1,3}$ $D_{2,1}$ $D_{3,3}$ $D_{4,3}$
C_3	$S_{1,2}$ $S_{2,3}$ $S_{3,2}$ $S_{4,3}$	$D_{1,3}$ $D_{2,1}$ $D_{3,3}$ $D_{4,2}$
C_4	$S_{1,1}$ $S_{2,2}$ $S_{3,1}$ $S_{4,2}$	$D_{1,3}$ $D_{2,3}$ $D_{3,2}$ $D_{4,2}$
C_5	$S_{1,1}$ $S_{2,1}$ $S_{3,1}$ $S_{4,1}$	$D_{1,3}$ $D_{2,3}$ $D_{3,1}$ $D_{4,1}$

*The first subscript indicates tactor number, and the second subscript indicates tactor level.

4.2.1 Subject Training

During training, subjects saw the virtual hand on the computer screen moving as the tactors vibrated. Training began by activating only one tactor at a time. Each tactor encoded a hand motion, broken down into three levels (Figure 2). For each tactor, the virtual hand moved through the specified hand motion several times as the tactor levels changed sequentially. The experimenter informed the subject how the hand was moving and how the levels related to the movement.

Next, subjects trained on C_1-C_5 in sequential order (Figure 5), going through the entire set of configurations twice. Table I gives the rendered tactor patterns for each hand configuration, and all four tactors were activated during this part of training. The virtual hand started at a reference configuration, C_0, and then transitioned into one of C_1-C_5. During the first iteration through the set of hand configurations, subjects were given as much time as desired to discriminate tactor levels and think about the mapping. During the second iteration, the time allotted for the same tactor identification task was reduced to 10 seconds.

4.2.2 Testing

Five trials were tested for each hand configuration, C_1-C_5, pseudo-randomly distributed, resulting in a total of 25 testing trials. During testing, images of C_1-C_5 were displayed on the computer screen at all times.

Subjects wore noise-cancelling headphones or headphones playing white noise during testing to mask any sounds from the tactors and noises in the room. Each tactile rendering started at C_0 and then transitioned into one of C_1-C_5. The tactors continued to vibrate until subjects chose one of the five hand configurations displayed on the screen. Subjects also identified the tactor level they felt for each tactor, reporting an overall tactor pattern on the second and fourth trial for each hand configuration. A total of 10 trials were tested that indicated overall tactor pattern. All tactors were turned off briefly between each trial.

During testing, subjects were encouraged to take as much time as needed to make a decision. Subjects were not aware that time until response was recorded for each trial. Subjects were given no indication of whether their answers were correct during testing. At

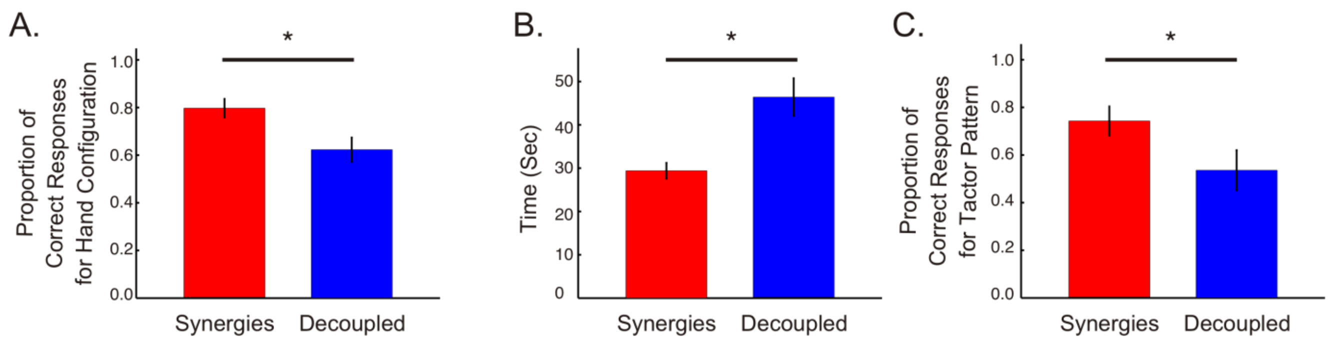

Figure 6: Presented are mean values as indicated by the maximum height of the red and blue bars, and one standard error of the mean as indicated by the black error bars. **A.** Hand configuration accuracy was significantly higher for Synergies than Decoupled [$F(1,12) = 16.91$, $p = 0.001$]. **B.** Time elapsed while identifying grasp was significantly less for Synergies than Decoupled [$F(1,12) = 26.67$, $p = 0.0002$]. **C.** Tactor pattern recognition accuracy was significantly better for Synergies than Decoupled [$F(1,12) = 6.72$, $p = 0.023$].

the completion of each session, subjects completed a short survey to assess the difficulty of the task and offer comments.

5 Results

Subject performance was compared for the Synergies and Decoupled mappings using several metrics: identification of correct hand configuration, elapsed time, and correct identification of tactor vibration levels. Additionally, the relationship between discriminating hand configuration and tactor vibration patterns was investigated, as well as learning effects. Below these results and findings based on the survey are given.

5.1 Hand Configuration Accuracy

The proportion of correctly identified hand configurations out of the 25 trials was calculated for each subject within each method, and then the individual subject proportions were averaged together. Subjects achieved a 79.7% success rate with Synergies and a 62.3% success rate with Decoupled (Figure 6A). A repeated-measures 2-way analysis of variance (ANOVA) showed that subjects were significantly better at identifying hand configurations using the Synergies method than the Decoupled method [$F(1,12) = 16.91$, $p = 0.001$]. Figure 7 shows confusion matrices for the Synergies (Figure 7A) and Decoupled (Figure 7B) mappings, respectively. The matrices summarize for all subjects the proportion of correctly reported hand configurations (diagonal elements) and the incorrectly reported hand configuration chosen for each actual hand configuration (off-diagonal elements).

5.2 Elapsed Time to Identify Hand Configuration

Time to identify a hand configuration was calculated as the number of seconds from the initiation of the rendering to when the subject made a decision about the hand configuration. If the administrator requested the subject to identify a tactor pattern, the additional time to do so was not included in the time to identify a hand configuration. Elapsed time was averaged across all 25 trials for each subject within each method, and subject averages were subsequently averaged. For the Synergies method, subjects took an average of 29.4 seconds to identify a hand configuration. Using the Decoupled method, hand configurations were identified in an average of 46.4 seconds (Figure 6B). A repeated-measures 2-way ANOVA found that Synergies took significantly less elapsed time than Decoupled [$F(1,12) = 26.67$, $p = 0.0002$].

5.3 Tactor Pattern Discrimination Capabilities

The proportion of correctly identified tactor patterns out of the 10 trials was calculated for each subject within each method, and averaged across subjects. Subjects correctly identified the tactor pattern an average of 74.3% of the time with the Synergies method and 53.6% with the Decoupled method (Figure 6C), and a repeated-measures 2-way ANOVA found that tactor pattern accuracy was significantly better for Synergies than Decoupled [$F(1,12) = 6.72$, $p = 0.023$].

Table II shows the relationship between the ability to correctly discriminate tactor patterns and the ability to discriminate hand configurations for both the Synergies (II.A) and Decoupled (II.B) methods. Proportions for the 10 trials when subjects reported hand configuration and tactor pattern correctly and incorrectly are given. For both methods, Correct/Correct was the highest of all four categories with a proportion of 0.686 for Synergies, and 0.464 for Decoupled. Both proportions are much higher than chance (0.00247), indicating that subjects can identify the correct

A. Synergies Confusion Matrix

Actual Hand Configuration	Reported Hand Configuration				
	C_1	C_2	C_3	C_4	C_5
C_1	0.6429	0	0.2000	0.1286	0.0286
C_2	0.0143	0.9714	0	0.0143	0
C_3	0.0857	0.1286	0.6857	0.1000	0
C_4	0.0714	0.0143	0.0429	0.8143	0.0571
C_5	0	0	0	0	1.000

B. Decoupled Confusion Matrix

Actual Hand Configuration	Reported Hand Configuration				
	C_1	C_2	C_3	C_4	C_5
C_1	0.4000	0.0143	0.3429	0.1714	0.1000
C_2	0.0143	0.8714	0.0714	0.0286	0.0143
C_3	0.2857	0.0571	0.5286	0.0571	0.0714
C_4	0.1429	0.0571	.0143	0.6571	0.1000
C_5	0.0714	0.0286	0.0429	0.2000	0.6571

Figure 7: Confusion matrices indicating the proportions of correctly reported hand configurations across the row for each of the actual tested hand configurations. Darker shading indicates a larger proportion. If the subjects responded perfectly, all diagonal elements would be black and off-diagonal elements would be white. **A.** Confusion matrix for Synergies. **B.** Confusion matrix for Decoupled.

Table II. Relationship between correctly discriminating tactor pattern and correctly discriminating hand configuration. Each box shows the proportion averaged across subjects for the 10 trials where subjects reported both hand configuration and tactor pattern.

A. Synergies

Tactor Pattern Accuracy	Hand Configuration Accuracy: Correct	Hand Configuration Accuracy: Incorrect	Totals
Correct	0.686	0.057	0.743
Incorrect	0.107	0.150	0.257
Totals	0.793	0.207	

B. Decoupled

Tactor Pattern Accuracy	Hand Configuration Accuracy: Correct	Hand Configuration Accuracy: Incorrect	Totals
Correct	0.464	0.072	0.536
Incorrect	0.164	0.300	0.464
Totals	0.628	0.372	

tactor levels and furthermore the correct hand configuration. Correct/Incorrect and Incorrect/Correct were small for both methods. The last category, Incorrect/Incorrect, was greater for the Decoupled method than the Synergies method.

5.4 Learning Effects

Learning effects on hand configuration accuracy were investigated within each group using a repeated-measures 2-way ANOVA (2 groups x 2 days). Hand configuration accuracy was significantly higher on Day 2 than Day 1 [$F(1,12) = 6.91$, $p = 0.022$]. Additionally, subjects who were taught Decoupled first significantly outperformed subjects taught Synergies first over both days of testing [$F(1,12) = 5.15$, $p = 0.042$].

A significant interaction effect of day and group was also found [$F(1,12) = 16.91$, $p = 0.001$]. A post-hoc Scheffé test was run on the interaction. Subjects who began with Decoupled on Day 1 saw significant improvement on Day 2 with Synergies [$p = 0.004$]; those who began with Synergies on Day 1 were not found to perform differently on Day 2 with Decoupled [$p = 0.77$]. Additionally, subjects who began with Decoupled on Day 2 were not found to perform differently than those who began with Decoupled on Day 1 [$p = 0.95$]. In contrast, subjects who began with Synergies on Day 2 outperformed those who began with Synergies on Day 1 [$p = 0.030$]. Figure 8 shows these results graphically, breaking down performance over Day 1 and Day 2 into the further subgroups of Synergies and Decoupled.

5.5 Subject Comments

In the survey completed at the end of each session, subjects described the challenges they felt when discriminating the different carrier frequencies of a given hand configuration. Subjects mentioned that they would have preferred a reference carrier frequency signal when they were choosing between the different hand configurations during testing. Most subjects said that it was difficult to discriminate among all four tactors, especially considering that the tactors were vibrating continuously and out of phase. Several subjects noted that they would have preferred to have the tactors in phase, and also noted that they became desensitized to the vibrations over the course of the experiment. Subjects noted that tactors on the left and right abdomen (Tactors 2 and 3, respectively) were the most difficult to discern, especially through thicker shirts. Some subjects also needed extra time during training to acclimate to the tickling sensation they felt from the vibrations of the tactors.

6 Discussion

Results indicate that both Synergies and Decoupled are viable methods of mapping vibrotactile feedback to proprioceptive

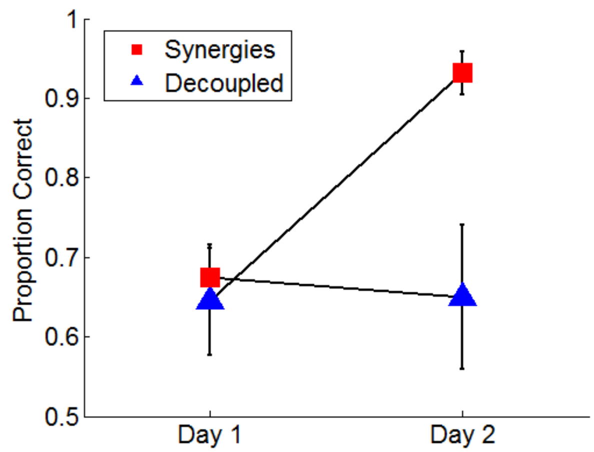

Figure 8: Hand configuration accuracy by day and method. Lines connect Day 1 and Day 2 performance within each group. A repeated-measures 2-way ANOVA showed a significant interaction effect of day and method [$F(1,12) = 16.91$, $p = 0.001$]. Synergies Day 2 performance is significantly better than all other day/method combinations (post-hoc Scheffé test, $p < 0.05$). All error bars indicate one standard error of the mean.

information of one's hand, however both require a lengthy amount of time to interpret the feedback. We discuss the results below.

6.1 Variability Effects

Users performed significantly better with the Synergies method than the Decoupled method for all calculated metrics: hand configuration accuracy, elapsed time while identifying hand configuration, and tactor pattern discrimination. We believe this is because the set of tactor patterns used in the Decoupled method lacks variability as compared to the Synergies method. In order to quantify this claim, we identified the number of tactors that are at different levels between each of the 10 pairs of hand configurations. Figure 9 illustrates this variability with confusion matrices. The entries were generated by examining a pair of hand configurations in Table I and counting how many tactors were rendering different levels.

As indicated in Figure 9, the Synergies mapping exhibits greater variability than the Decoupled mapping; all hand configurations differ by at least two tactors and four pairs of hand configurations differ with respect to all four tactors. The Decoupled method has three different hand configuration pairings that differ with respect to only one tactor and none which differ with respect to all four tactors. Additionally, the first tactor does not vary at all between any of the hand configurations rendered using the Decoupled

A. Synergies Tactor Variability

		Hand Configuration				
		C_1	C_2	C_3	C_4	C_5
Hand Configuration	C_1	0	3	2	2	3
	C_2	3	0	2	4	4
	C_3	2	2	0	4	4
	C_4	2	4	4	0	2
	C_5	3	4	4	2	0

B. Decoupled Tactor Variability

		Hand Configuration				
		C_1	C_2	C_3	C_4	C_5
Hand Configuration	C_1	0	2	1	1	3
	C_2	2	0	1	2	3
	C_3	1	1	0	2	3
	C_4	1	2	2	0	2
	C_5	3	3	3	2	0

Figure 9: Confusion matrices indicating the variability in tactor levels between two hand configurations. Variability is identified as the number of tactors rendering different levels between the two hand configurations. Darker shading indicates a greater variability between a pair of hand configurations. Ideally the off-diagonal elements have entry = 4, indicating that all four tactors are at comparatively different levels between the two hand postures. **A.** Synergies confusion matrix. **B.** Decoupled confusion matrix.

method (Table I). The three pairings of hand configurations for the Decoupled method that differed by a single tactor (C_1 vs. C_3, C_1 vs. C_4, C_2 vs. C_3) were also the largest off-diagonal data entries in the confusion matrix (Figure 7). In this sense, subjects were more likely to mistake the hand configurations in these pairings for each other than in the other "more variable" pairings.

Increased variability in tactor renderings between pairs of hand configurations may contribute to the increased hand configuration identification accuracy observed with the Synergies mapping. This could also account for the shorter elapsed times for subjects to choose a hand configuration in the Synergies method.

6.2 Discrimination of Tactor Patterns and Hand Configurations

There are two different ways in which subjects could perform our task. One way is for subjects to memorize the hard-coded one-to-one correspondence between the five tactor patterns and five hand configurations. This approach relies on relating the aggregate feeling of all four tactors to a known hand configuration, without necessarily understanding *why* the tactor pattern corresponds to that particular hand configuration. As such, the performance level when using this approach would rely heavily on the variability across tactor patterns (Section 6.1), but would *not* rely heavily on learning the specific mapping strategy. In other words, it does not matter if one mapping is more intuitive than the other because an understanding of the mappings is not important for being able to memorize each tactor pattern.

Another approach is to isolate the signal felt from each individual tactor, and to fully learn the mapping between each tactor and the corresponding hand motion. With this approach, the ability to understand a mapping is very important. Which of the two approaches subjects chose was beyond our control, and furthermore, our experimental design does not distinguish between them. We encouraged subjects to employ the latter method in order to promote robustness—we wanted subjects to learn a system that would allow them to recognize novel hand positions, even though we did not explicitly test this. Overwhelmingly, however, most subjects acknowledged afterwards that they used the former method because it was much easier to memorize. This implies that the difference in tactor pattern variability between Decoupled and Synergy mappings is the main cause of the different performance levels.

To verify this, we investigated Table II further. Decoupled Incorrect/Incorrect is significantly greater than Synergies Incorrect/Incorrect. Looking at Decoupled Incorrect/Incorrect, in over half of those trials subjects reported the tactor pattern of a different hand configuration than the one rendered to them; however, they reported the appropriate hand configuration based on the erroneously reported tactor pattern (e.g., if C_1 is rendered as $D_{1,3}$ $D_{2,1}$ $D_{3,2}$ $D_{4,2}$ but the subject reports $D_{1,3}$ $D_{2,1}$ $D_{3,3}$ $D_{4,2}$, then choosing C_3 is the appropriate response based off of the reported levels). Interestingly, this did not occur often for Synergies Incorrect/Incorrect.

Motivated by the last finding, we further considered the subset of trials in which the reported tactor patterns matched one of the five target tactor patterns, regardless of whether or not the reported pattern was correct. In 81% of such Synergies trials and 71% of Decoupled trials, subjects reported the hand configuration that correctly corresponded with the reported tactor pattern; however, the accuracy was not significantly different between the two methods, as noted by a two-sided t-test [$p=0.1379$]. Thus, the mapping from the *perceived* tactor pattern to reported hand configuration is similar for both methods. The superiority of the Synergies method, therefore, can be attributed to its better accuracy in reported tactor pattern (see Section 6.1). We conclude that the basis of the reported differences between Synergies and Decoupled relies heavily on the differences in perception of tactor patterns between the methods, and not necessarily the mapping itself.

6.3 Learning Effects

Subjects who first trained with Decoupled outperformed those who were first taught Synergies over the two-day period. An interpretation for this finding, consistent with an earlier discussion, is the limited variability in tactor patterns between different hand configurations for the Decoupled method. Subjects perhaps focused on the subtleties of the tactor patterns, and this skill easily transferred to hand configurations decomposed into Synergies. In contrast, the more variable tactor patterns in the Synergies method led subjects to classify some hand configurations as "all tactors going fast" or "all tactors going slow", which is not the constructive method for determining hand configuration, as emphasized in training. This idea is consistent with subject commentary.

7 Conclusions and Future Work

This work shows that it is possible to use haptic feedback, in particular vibrotactile feedback around the torso, to convey information about complex hand configuration in a simplified manner, although the amount of time to achieve this using the tested methods is lengthy. Two methods were used to map a tactor vibration pattern to a hand configuration: Synergies and Decoupled. After testing 14 subjects over the course of two days, it was found that subjects identified correct hand configuration significantly better using the Synergies mapping than the Decoupled mapping, and that the Decoupled mapping encouraged learning while the Synergies mapping did not. Synergies is believed to outperform Decoupled because it has more variability in its tactor patterns. Further analysis showed that both methods resulted in equal performance for correctly identifying hand configuration, so the errors must have occurred when converting tactor pattern into hand configuration.

Future work could look into the effects of learning and training on performance. With more training and testing, we can determine whether learning individual tactor to hand motion mappings is a viable method, or whether subjects prefer to use the overall feeling from all tactors. While the former is preferable for generalization to novel hand configurations, the latter may be less taxing in daily use. Additionally, devices other than vibrotactile elements could be used to stimulate the skin so that irritation and loss of sensation over time will not occur.

In order to more directly assess the effect of tactor pattern variability, we could normalize the variability between the two methods. Several subjects mentioned that although the Decoupled method was easier to learn, the specific patterns in Synergies were easier to recognize due to their variability. However, it is possible that with respect to our five chosen hand configurations, the Decoupled method cannot express the full variability in tactor patterns that is inherent to the Synergies method. Although both methods are orthogonal, synergies, by definition, most optimally spans the hand motion variance. Therefore, it is no surprise that the hand configurations C_1-C_5 that we chose to test are more effectively represented by the Synergies method.

Finally, while performance levels were promising in this study, the response times of our subjects were too long for practical use. Future work will have to address this issue if this apporach is to be considered seriously for prosthetic use.

Although we tested a limited subset of all possible hand configurations, the ideal design of a haptic feedback system for prosthesis configuration display would account for all possible hand configurations. The results for Synergies, in particular, are encouraging, motivating future work on synergy-based haptic feedback.

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