Static and dynamic proprioceptive recognition through vibrotactile stimulation

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Abstract

Objective. Proprioceptive information provides individuals with a sense of our limb’s static position and dynamic movement. Impaired or a lack of such feedback can diminish our ability to perform dexterous motions with our biological limbs or assistive devices. Here we seek to determine whether both static and dynamic components of proprioception can be recognized using variation of the spatial and temporal components of vibrotactile feedback.

Approach. An array of five vibrotactors was placed on the forearm of each subject. Each tactor was encoded to represent one of the five forearm postures. Vibratory stimulus was elicited to convey the static position and movement of the forearm. Four experimental blocks were performed to test each subject’s recognition of a forearm’s simulated static position, rotational amplitude, rotational amplitude and direction, and rotational speed.

Main results. Our results showed that the subjects were able to perform proprioceptive recognition based on the delivered vibrotactile information. Specifically, rotational amplitude recognition resulted in the highest level of accuracy (99.0%), while the recognition accuracy of the static position and the rotational amplitude-direction was the lowest (91.7% and 90.8%, respectively). Nevertheless, all proprioceptive properties were perceived with >90% accuracy, indicating that the implemented vibrotactile encoding scheme could effectively provide proprioceptive information to the users.

Significance. The outcomes suggest that information pertaining to static and dynamic aspects of proprioception can be accurately delivered using an array of vibrotactors. This feedback approach could be used to potentially evaluate the sensorimotor integration processes during human–machine interactions, and to improve sensory feedback in clinical populations with somatosensory impairments.

1. Introduction

An integral part of daily motor functions lies in the use of sensory feedback. Proprioceptive feedback provides individuals with critical information regarding the state of the body such as its position and movement [1–3]. Proprioception is transmitted largely by primary afferent fibers innervating muscle spindles, with a sense of limb static position (position sense) from primary and secondary afferent and a sense of dynamic movement (kinesthesia) largely from primary afferent [4]. There are also contributions from mechanoreceptors in joint capsules and cutaneous tactile receptors during skin stretch near the joint [5]. Internal representations of the body and peripersonal space rely heavily on proprioceptive information during the planning, execution, and learning of a desired task [6].

Impaired or a lack of proprioceptive can limit the control of an individual’s limb [7–11] or assistive device [12–15] when relying exclusively on vision. The amount of proprioceptive feedback delivered to an assistive device user varies based on the system. Many current devices provide little to no insight about the current state of the device [16]. Additionally, individuals with sensory impairments, such
as many stroke survivors [17], experience a loss of 
proprioception resulting in an inability to perceive 
their limb’s position or movement. For example, 
significant correlation between upper limb motor 
and somatosensory impairments has been reported 
[10, 18–20]. This correlation suggests that underlying 
somatosenory impairments, including diminished 
tactile and proprioceptive sensations, can negatively 
affect an individual’s ability to perform motor tasks 
[8, 21]. In addition, somatosensory impairments can 
affect the performance of daily functional tasks due 
to the subject’s inability to correctly time and adjust 
their limb position, movement, or interaction with 
their surroundings [22].

To overcome these losses, several studies have 
implemented sensory substitutional techniques that 
provide vibrrotactile, electrotactile, or mechanotactile 
stimulation to the skin surface of the users [23–30]. 
Such information can also be delivered invasively 
through direct nerve stimulation [31, 32]. In these 
studies, the stimulus provides information about 
the finger grip force, finger’s aperture, or a given joint’s 
position. These approaches have been shown to allow 
individuals to perceive joint postures with similar 
levels of success; however, the greater acceptance of 
noninvasive stimulation and its minimal risk can 
facilitate wide applications, such as the use of assistive 
or teleoperated devices. Nonetheless, position sense, 
in many of these cases, is encoded using varied stim-
ulus levels that each depict a given joint angle or 
posture.

Although these studies have proven to be 
beneficial, the explicit approach to deliver the feed-
back could limit the quality of the information. For 
example, the use of a single stimulation site can res-
ult in a lower number of distinguishable sensation 
levels, which can reduce the number of joint angles/
postures that can be sensed. Attenuation/adaption 
of the perceived information may arise due to con-
tinuous and repetitive stimulation at a single loca-
tion [33–36]. Eliciting proprioceptive information 
using an array of vibrotactors has been examined in 
recent work [37]; however, few studies have individu-
ally evaluated different aspects of evoked proprioce-
ption in its entirety involving both position sense and 
kinesthesia. The use of sensory substitutional tech-
niques to describe kinesthesia has yet to be explored 
to the same extent, especially in cases where the stim-
ulus describes an individual’s forearm orientation. 
Proprioceptive information of a biological limb or 
assistive device in terms of static posture, movement 
accuracy of different aspects of artificial proprioce-
ption that can describe both static and dynamic prop-
eries. All components of proprioception were evoked 
using a single modality that can reduce the instability 
of the feedback by utilizing a location-based encoding 
scheme. The sensory encoding strategies examined 
here can be used to provide proprioceptive feedback 
to users of various prosthetic limbs and teleoperated 
deVICES. The outcomes can allow us to readily evaluate 
the sensorimotor integration processes in the control 
of these devices in order to improve the user’s dexter-
ity and confidence. Additionally, future implementa-
tion of this strategy can be beneficial to restoring sen-
sory function and to rehabilitative training of clinical 
populations with somatosensory impairments.

2. Methods

2.1. Subjects

Six neurologically intact subjects (six males, 20– 
32 years of age) participated in this study. Each indi-
vidual gave informed consent via protocols approved 
by the Institutional Review Board of the University of 
North Carolina at Chapel Hill.

2.2. Experimental set-up

Upon arrival, subjects were seated in front of a table 
with one forearm, based on the subject’s preference, 
comfortably placed upon it in a neutral position. 
The experimenter measured the length of the sub-
ject’s forearm along its anterior side from the bot-
tom of the palm to the proximal edge of the ante-
cubital fossa. The band of vibrotactors was placed 
to a third of its length from the proximal end. Table 1 
depicts each subject’s forearm length and circumfer-
ence, resulting in an average and standard deviation 
of 26.52 ± 1.02 cm and 25.67 ± 0.99 cm, respectively. 
The band consisting of five tactors (C-2 Tactor, ATAC 
Technology) was then wrapped around the subject’s 
forearm (figure 1(A)). Each of the five tactors are 
3.05 cm in diameter and were spaced 5 cm apart 
center-to-center) from one another (figure 1(B)). An 
inter-tactor distance of 5 cm was selected because it 
was greater than the reported spatial acuity of the
forearm (3 cm) [38] and could be used across subjects of varied forearm dimensions. Due to the tactor size, inter-tactor distances of less than 5 cm (e.g. 3 or 4 cm) would result in either the tactors becoming in contact with one another or would result in inconsistent contact between the tactor’s vibratory element and the individual’s skin when the band was wrapped around radially smaller forearms. To ensure consistency across subjects, tactor 3 was first positioned on the radial side of the forearm. The band was then oriented so that tactors 1 and 2 were on the lateral side of the forearm, while tactors 4 and 5 were on the medial side (figure 1(C)). Once each tactor’s location was finalized, the band was tightened to ensure sufficient skin contact. Subjects were then asked to report any discomfort at this time and encouraged to report any future discomfort or occurrence of restrictive blood flow throughout the experiment.

Vibratory stimulation was elicited using a custom MATLAB (v2017a, MathWorks Inc. Natick, MA) interface. The interface communicated with an external universal controller (ATAC Technology) in order to specify the vibration timing, amplitude, and frequency for each tactor. Although amplitude and frequency could be modified, these parameters were fixed at values of 225 mA RMS and 200 Hz, respectively. An amplitude that elicited clear sensation without any discomfort was determined through preliminary testing. The frequency was chosen based on previous work which showed that human skin was most responsive to frequencies between 200 and 250 Hz [4]. Five tactors were implemented in order to signify the five forearm orientation postures of interest as shown in figure 1(C). This setup was selected to provide the user with information for both postural (static position) and kinesthesia (dynamic movement) perception. In addition, the setup minimized the potential for skin irritation and desensitization caused by continuous stimulation of a single tactor at multiple stimulus levels.

To encode proprioception in terms of postural position and kinesthesia, each tactor placed on the subject’s forearm corresponded to a given forearm orientation. Forearm posture was broken into five orientations: full supination around 90°, partial supination around 45°, neutral around 0°, partial pronation around 45°, and full pronation around 90°. Each of these postures were paired with a specified tactor from one to five, respectively (figure 1(C)). A postural position could be determined based on a specific active tactor, while kinesthesia was encoded based on how the vibrotactile stimulus transitioned from one tactor to the next. By interpreting the delivered stimulus in this manner, each subject could discriminate various static forearm positions, dynamic movement amplitudes, directions, and speeds. These four properties describing forearm rotational movement were evaluated to determine the subject’s ability to perceive individual components of proprioception. The four parameters can then be combined to give comprehensive state of the joint during static posture and dynamic movements.

### 2.3. Procedure

Following the placement of the vibrotactor band, each tactor was activated to ensure that none of them evoked a stimulus that caused pain or discomfort to the individual. Additionally, subjects were asked to correlate each tactor with a designated forearm posture. During the experimental trials, the subjects were position with their forearm in a neutral position and were instructed to avoid voluntary movement of the forearm. Auditory and visual information pertaining to the stimulation was blocked to avoid potential bias by providing other sensory modalities of information to the user. Auditory input was blocked using noise-canceling headphones, while visual information was removed by placing the forearm out of the subject’s line of sight.

The main experiment was composed of two sessions each with four blocks that tested an individual’s ability to discern the delivered stimulus as it pertained to forearm static position or movement amplitude, direction, and speed (figure 2) without voluntary movement of the forearm. The first session (single task) identified the recognition accuracy of the evoked vibratory percept during each of the four blocks. All six subjects participated in this session. During the second session (dual task), recognition accuracy was assessed as three subjects (subjects 1, 4, and 6) attempted to discern the evoked vibratory feedback while performing an additional cognitive task (figure S1 of the supplementary material (available online at stacks.iop.org/JNE/18/046093/mmedia)). During the cognitive task, a sequence of five random colors was displayed on a computer screen in front of each subject. Subjects were expected to memorize each color and its position in the sequence, and report a color (randomly picked by the experimenter) at the end of each trial. Specifically, using a visual cue, subjects were informed that the trial would begin in 3 s to ensure that they were ready for the upcoming
Figure 1. Diagram illustrating the placement of the band of vibrotactors on the forearm (A), the arrangement and spacing between the tactors along the band (B), and their given location in relation to the right forearm of the subjects (C). Each of the five tactors corresponded to a distinct forearm position that included full and partial supination, neutral position, and partial and full pronation.

Figure 2. Diagram illustrating the four blocks implemented to test each subject's ability to recognize a forearm static position (B1), dynamic rotation amplitude (B2), rotation amplitude and direction (B3), and rotation speed (B4) based on the delivered vibrotactile feedback.

During each trial, each color and corresponding position number was displayed for 2 s in a sequential order based on a randomized sequence. The random sequence allowed for repetitions, and was constructed by pulling from a pool of seven distinct colors. After five colors were displayed, a 2 s break was provided before the display prompted them to report the color of the nth ($n = 1–5$) word among
the sequence. At this time, subjects were asked to identify the random color and the perceived vibratory feedback for the trial. During the dual task, the vibratory stimulus began at a random time following the start of the cognitive task, while the stimulation duration varied based on the experimental block. Baseline evaluations involving only the cognitive task were performed by the subjects. All subjects that performed session 2 confirmed they had no color vision deficiencies.

For each block within the experiment, subjects were given the opportunity to familiarize themselves with the experimental conditions. This included the replaying of all tactor positions in blocks 1–3 and giving example transitions for each speed in block 4. Following the familiarization phase, a short training period was allotted for each block that involved the performance of 5–10 random representative trials, depending on each subject’s confidence. These trials were the only time where subjects were given feedback about their response.

The first block 'Position Sense' evaluated the subject’s ability to recognize forearm static position. During this block, one of the five tactors elicited a 2 s vibratory stimulation to the individual. Following the stimulation, the subject was asked to report the perceived forearm position as either full supination, partial supination, neutral position, partial pronation, or full pronation. A total of 20 trials involving all the possible positions (5 positions × 4 repetitions) were evaluated.

The second block 'Rotation Amplitude Sense' evaluated the recognition of a dynamic movement amplitude that began at full supination or pronation. To evoke a sense of rotation, the stimulus continuously transitioned to its adjacent tactors until a random final position was reached. During these trials, stimulation was elicited for 1 s per tactor and concluded when the final tactor had been activated. Following the conclusion of each trial, the subject was asked to identify the movement amplitude, or the displacement of the forearm in terms of number of forearm positions in which the stimulus surpassed, using a discrete value of 1, 2, 3, or 4. This block was composed of a total of 20 trials (5 amplitudes × 2 directions × 2 repetitions).

The third block 'Rotation Amplitude and Direction' evaluated the recognition of movement amplitude and direction that involved a random starting and ending position. For a given trial, stimulation was initially evoked at a random tactor with the stimulus transitioning to different adjacent tactors in potential given direction until a final position was reached. Similar to block 2, stimulation at each tactor lasted for 1 s. At the end of the trial, the subject was asked to identify the movement amplitude and direction by reporting the starting and ending forearm position as either full supination, partial supination, neutral position, partial pronation, or full pronation. A total of 20 trials were performed involving all potential combinations of starting and ending positions.

The final block 'Rotation Speed Sense' evaluated the recognition of forearm rotation speed. The starting and ending position were set to either full supination or full pronation in order to simulate the full range of motion in either direction. Rotation speed was portrayed by adjusting the stimulation duration for all five tactors during a given trial. The vibratory sensation shifted along the subject’s arm as the stimulus transitioned from one tactor to the next with only a single tactor being activated at a given time. Three rotation speeds (18, 28.8, and 72 degrees per second) were implemented with each representing a low, medium, and high speed, respectively. The speeds were determined based on the speed required to rotate 180° when each of the five tactors’ stimulation duration lasted 2, 1.25, or 0.5 s. Due to the inverse proportionality of rotation speed and stimulation time, either time or rotation speed, but not both, could be evenly distributed. Evenly distributing time was selected here since the participants were discerning speed based on timing of the vibratory stimulus as it transitioned between tactors. At the end of each trial, the subjects reported their perception of the forearm rotation speed (low, medium, or high speed). This block contained 18 trials (3 speeds × 2 directions × 3 repetitions).

Different blocks were randomized for each subject. For each block, the trial conditions were selected from a randomized pool, resulting in a double-blinded test. Throughout the experiment, 10 s of rest time was provided between trials, while 3–5 min of rest was provided between blocks.

2.4. Data analyses
To determine the accuracy of the proprioceptive discrimination, confusion matrices were created that compared the actual delivered stimuli against the perceived stimuli across all subjects. Each matrix depicts the level of accuracy for each task as well as the instances of errors occurred. The variability and distribution of the errors across all subjects were also analyzed for a given experimental condition.

2.5. Statistical analyses
One sample t-tests were implemented to determine if the recognition accuracies for each block within session 1 were found to be significantly greater than chance values. In most cases, the results concluded with accuracies that were close to the upper bound of 1. To account for the rightly skewed distribution of the data, a logit transformation was applied prior to the performance of the statistical analysis to ensure a normal distribution of the residual [39]. For the four blocks, the random chance value of accurately identifying the static position, amplitude, amplitude and
3. Results

3.1. Position sense of session 1
For the position sense block, each subject reported the perceived forearm static position based on the tactor stimulus. Figure 3(A) shows the confusion matrix that compared the actual and perceived forearm position across all subjects during session 1. The results showed that subjects could identify the forearm position when the stimulus was delivered by a single tactor. All errors were found to be caused by confusion among adjacent tactors, especially those located along the lateral side of the individual’s forearm. When evaluating the individual subject errors (figure 3(B)), errors were observed across four of the six subjects with the majority reported in subjects 3, 5, and 6. Nevertheless, the results showed that recognition of static position could be performed at an accuracy and standard error of 91.7 ± 3.3% across all subjects, which was significantly greater than the chance value \((p < 0.001)\). In addition, recognition of an individual static position could be performed with accuracies significantly greater than chance \((p < 0.001)\).

3.2. Rotation amplitude sense of session 1
For the rotation amplitude sense task, subjects determined the final forearm position when stimuli transitioned between adjacent tactors representing a dynamic movement. The confusion matrix in figure 4 illustrates the recognition results across all subjects. The results showed that subjects were able to discern the rotation amplitude correctly in 119 out of 120 trials, resulting in an accuracy of 99.0 ± 1.0%. Additionally, the recognition performance across subjects was found to be significantly greater than the chance level \((p < 0.001)\).

3.3. Rotation amplitude and direction of session 1
Figure 5 shows two confusion matrices that summarized the recognition performance across all subjects. The results showed that subjects correctly identified the dynamic movement (figure 5(A)) in 109 out of 120 trials, resulting in an accuracy of 90.8 ± 2.4%. Contrarily, figure 5(C) shows that subjects correctly identified simply the rotation amplitude and direction in 117 out of 120 trials, resulting in an accuracy of 97.5 ± 2.74%. This indicates that errors mostly arose from dynamic movements being correctly perceived in terms of the amplitude and direction of the movement, but incorrect in the identification of the starting and ending posture (figure 5(D) versus figure 5(B)). In these cases, most errors occurred when the subject perceived a given movement, i.e. starting/ending posture, as being shifted by a single tactor in either direction. When evaluating the individual subject errors (figure 5(B)), all subjects, except subject 2, responded inaccurately at least twice but no more than three times for a given subject, resulting in individual subject accuracies >85%. In addition, when errors were caused by a misidentification of the amplitude and direction, it should be noted that all errors resulted from the misidentification of the starting posture rather than the ending posture. Nonetheless, the majority of trials were correctly identified resulting in an overall accuracy significantly greater than chance \((p < 0.001)\).

3.4. Rotation speed sense results of session 1
For the rotation speed sense block, the subjects identified the speed in which stimuli transitioned between...
Figure 4. Confusion matrix quantifying the percentage of instances when comparing the perceived rotation amplitude with the ground truth during session 1. The numbers ’1–4’ indicate the amplitude of each movement with 1 signifying a transition to an adjacent posture and 4 signifying a transition from full supination to full pronation, or vice versa.

Figure 5. Confusion matrices quantifying the percentage of instances when comparing the perceived dynamic movement (A) and perceived rotation amplitude and direction (C) with the ground truth during movements involving random starting and final forearm positions in session 1. Individual subject errors for each condition are shown in panel (B) and (D), respectively. In panel (A) and (B), ’1’ corresponds to full supination, ’2’ corresponds to partial supination, ’3’ corresponds to neutral position, ’4’ corresponds to partial pronation, and ’5’ corresponds to full pronation. The pair of numbers indicate the starting and ending tactors for each trial. In panel (C) and (D), the numbers indicate the rotation amplitude with the direction depicted using a ’+’ or ’-’. ’n’ indicates the number of trials for each condition. Note: percent errors of 16.7 and 5.6 reported in part (C) each indicate that a single trial was incorrectly perceived per rotation amplitude and direction.
adjacent tactors at different speeds. The confusion matrix in figure 6(A) shows the recognition results across all subjects. The results showed that the rotation speed was correctly identified in a majority of the trials (103 out of 108), with an accuracy and standard error of 95.4 ± 1.7%, which was significantly greater than chance ($p < 0.001$). Errors only occurred when subjects tried to discern the slow and medium rotation speeds (figure 6(B)). The fast rotation speed was correctly identified in all the trials.

3.5. Summary results of session 1
Figure 7 shows a summary evaluation of the overall accuracy and standard error for each block along with the accuracies from each individual subject (represented by circles). The summary results showed that the movement amplitude accuracy was the highest (99.0%) among the different conditions, and that the static position and the amplitude-direction accuracy were the lowest (91.7% and 90.8%, respectively), with a large inter-subject variation (approximately 80%–100%).

3.6. Comparison of accuracy between the single (session 1) and dual tasks (session 2)
Lastly, figure 7 also depicts the individual and average accuracy of session 2 from the three subjects. The overall accuracy did not differ substantially across the sessions. For blocks 1, 3, and 4, the subjects showed similar performance on recognizing the static position (93.3% in single task vs 94.9% in dual task), amplitude and direction of the simulated movement (90% in single task vs 88.4% in dual task), rotation speed (95.4% in single task vs 96.3% in dual task). For the rotation amplitude sense task, the overall accuracy from session 1 decreased from 99% to 95.8% following the addition of the cognitive task. Lastly, the accuracy of the cognitive task alone (baseline) for each block is illustrated in figure S6. The average color memorization accuracy was approximately 98.3 ± 1.7% in the cognitive task alone, while the memorization accuracy across the dual task blocks ranged from 92.6% to 98.3%. The similarity in accuracy suggested that the subjects could effectively perform both tasks and did not defer the cognitive task in favor of the primary task.

4. Discussion
This study sought to individually evaluate the perception accuracy of different aspects of evoked proprioceptive feedback (involving both position sense and kinesthesia) using an array of vibrotactors. The forearm’s static position, rotational amplitude, rotational direction, and rotational speed were encoded by the location of the stimulus and/or its transition across tactors during a given trial. Our results showed that different components of artificially evoked proprioception could be recognized with accuracies >90% during both single and dual tasks, indicating that both position sense and kinesthesia could be identified reliably using a single encoding scheme. The evoked proprioceptive information may be used to provide proprioceptive feedback that can restore sensory function to users of various assistive devices and clinical populations with somatosensory impairments.

Our results demonstrated that position sense recognition could be performed across all subjects with minimum training required. This suggests that the encoding scheme implemented was highly informative allowing the subjects to correctly identify the given static forearm posture in approximately 91.7% of the trials during session 1. This level of
Figure 7. Summary of recognition accuracies for the four experimental blocks during session 1 (single task) and session 2 (dual task). The average accuracy and standard error across the subjects are reported for both sessions, with a single asterisk indicating statistical significance ($p < 0.001$) during session 1 only. Statistical differences were not denoted for session 2 due to the small sample size. Each colored circle corresponds to the accuracy from a single subject.

accuracy was expected given that the spatial acuity of vibrotactile and touch feedback along the forearm is approximately 3 cm [38, 40]. Our results revealed that the majority of the errors resulted from the misidentification of the first and second tactors, which were positioned along the posterior side of the forearm and appeared to be more difficult to distinguish. Additional training or increased tactors-to-tactor separation could help improve the discrimination of the delivered stimuli, especially as vibratory spatial acuity has been shown to improve after prolonged training [41]. The delivered stimulus was also utilized to convey kinesthesia through the recognition of a forearm’s rotational speed, rotational amplitude, and rotational direction. Rotation speed recognition could be performed during this experiment; however, few errors arose from the misidentification of the slow and medium rotational speed. Similarly, a small number of errors arose from the misidentification of solely the rotation’s amplitude. The recognition accuracy was the lowest, when subjects discriminated both the amplitude and direction. Evaluation of the misidentified trials showed that the amplitude and direction were correctly reported in the majority of instances, instead the incorrect evaluation were caused by the inability to detect the correct pairs that corresponded to the given motion. This block resulted in a recognition accuracy similar to that reported for position sense recognition. Nevertheless, the recognition accuracy for each of the four blocks in session 1 was found to be substantially greater than chance. For session 2, the accuracy did not differ greatly from that of session 1. This indicates that the perception of the vibratory stimulus and the implemented encoding strategy was relatively easy to interpret allowing for little to no degradation in the accuracy of either the cognitive or vibratory perception tasks. Clearly, further investigations are necessary to quantify the cognitive load needed for the evoked sensory perception.

Adaptation can cause short-term reductions in cortical neuron sensitivity as a result of prolonged exposure to afferent stimulation. As the duration of exposure increases, the effects of adaptation, termed habituation, become larger and more severe, reducing an individual’s ability to accurately sense an elicited stimulus [33]. Habituation is our body’s innate ability to filter constant stimuli. Instead of perceiving continuous information, our brain filters out irrelevant stimuli until a conscious effort is made to perceive the filtered stimuli or perception of salient changes [36]. Separating forearm postures across various tactors limited the stimulation time on a single location. In doing so, this process reduced attenuation/adaptation and unintended habituation, which can improve the stability of the perception. If higher resolution or number of postures are required for a given task, more tactors can be added to improve the resolution of the system. Moreover, modification of the vibratory stimulus, in terms of stimulation gain and frequency, can also be used to further improve the resolution or can be implemented if the location of the band does not allow for additional tactors due to its limited space.

The feedback provided can be beneficial to individuals with sensory deficiencies. A synchronized somatosensory and motor training could benefit functional recovery during the rehabilitation of clinical populations that possess motor and/or sensory deficiencies. By pairing this system with a motor training task, amplified improvements may be
expected over time due to enhanced activation of both motor and sensory cortical regions. Clearly, future work is required to investigate this clinical effect.

This vibrotactile stimulation approach allowed individuals to recognize both the forearm’s position and movement. This encoding scheme can potentially provide proprioceptive information that can describe other joint movements as well. In particular, hand function requires both tactile and proprioceptive feedback to perform basic tasks. By integrating this setup with a system that provides tactile feedback [42–44], the delivered stimuli can elicit both types of feedback in real-time, which can lead to improvements in object manipulation and improve user acceptance and embodiment of assistive devices. Moreover, studies have shown that delivered information pertaining to two or more sensory modalities can successfully be interpreted [16, 17, 27]. Nevertheless, vibratory feedback is a form of sensory substitution that is unintuitive and can lead to greater cognitive burden compared with somatotopic feedback techniques. Prior work comparing somatotopic and non-somatotopic sensory feedback approaches has shown that non-somatotopic techniques lead to lower performance accuracies and greater completion times due to differences in sensation modality and location [45]. Contrarily, studies suggest that training can help reduce the added cognitive load caused by sensory substitutional techniques, leading to improved vibrotactile spatial acuity and intensity resolution [41]. Therefore, earlier studies have observed comparable task performance to somatotopic techniques [46–48], and improved prosthetic hand control with and without additional cognitive tasks [49, 50]. Although we have shown that recognition accuracy was not affected when performing dual tasks, the robustness of this approach should be assessed to validate that sensory overload or increased cognitive load does not negatively affect the performance of functional task in the real-world settings.

5. Limitations and future work

The current study has several limitations. First, when implementing this system in cases where continuous feedback is provided, it is still possible that adaptation and habituation may arise, if the limb is kept at a static position for long periods of time. In this study, stimulation at a single location was shorter than two seconds so the transition to a resting state was not implemented. To combat this, it was determined that if an orientation/posture was maintained for longer than 3–5 s, then the system would transition to a resting state. In this state, one second of vibratory stimulus would be delivered to provide users with posture feedback once every 10–20 s. The system would return to its normal state once movement was resumed. Therefore, the system continued to provide users of the static position of the forearm but limited the duration in which continuous stimulation was delivered to a single location. The ability to transition to a resting state is beneficial for individuals continuously using this system paired with their intact or assistive device during daily activities. Second, the recognition of various proprioceptive properties was tested on neurologically-intact individuals, but not on clinical populations. Several studies have found no difference in two-point discrimination and vibration threshold when comparing the perception from neurologically-intact limbs and amputated limbs [51] or reinnervated skin after targeted reinnervation [52]. When the stimulation approach is employed for upper limb amputees, there is possibility that the vibratory stimulus could induce motion artifacts within the recorded electromyography (EMG) signals. These disturbances can lead to inaccurate motor intent detection during myoelectric control of prostheses. However, we expect that the amount of disturbance would reduce if the tactors are placed far away (e.g. on the upper arm) from the EMG electrodes on the forearm. Additionally, the portable setup allows for the band to be placed on unaffected regions or regions with reduced sensory impairments in cases where vibration perception is limited along the forearm due to damaged afferent pathways. Vibratilc feedback has been successful in providing sensory information to stroke survivors [53, 54]. Nevertheless, future studies involving clinical populations would be required to ensure similar recognition results. Third, although the outcomes are promising, the number of participants and demographic representation across ages and gender is limited. The spatial acuity of the human forearm has been reported as being 3 cm or less across various groups of individuals [38]. The inter-tactor distance selected and the high levels of success suggest that these outcomes may potentially be translatable to other groups as well. Nonetheless, future work with a greater number of individuals across various demographics is required. Fourth, the subject’s posture could potentially affect their perception of a given percept. As the forearm posture changes, the geometry and biological characteristics of the muscles alters as well. In the current study, subjects were seated with their forearm in a neutral position. Although it is not expected that the spatial acuity should change as the forearm posture is altered, it is an important question that should be assessed in future work as there may be variability in tactor-skin contact affecting the perception of a given percept. Lastly, the current approach utilized vibratory profiles that kept frequency, intensity, and inter-tactor distance constant. In addition, when evaluating rotation speed, only three rotation speeds were evaluated. The purpose of this work was to highlight the ability to discern multiple aspects of proprioception (static and dynamic characteristics) by varying a single stimulation parameter (i.e. spatial location). Modifying the frequency and intensity together with
the vibratory location can potentially improve the perceptual resolution. Future evaluations will discern the perceptual resolution when modifying the frequency, intensity, and inter-tactor distance to identify the capabilities of this stimulation approach. In addition, the variability in forearm dimensions in this study was minimal, and as a result its effects should be assessed to discern if it impacts the spatial resolution of vibratory stimuli.

6. Conclusions

Overall, we demonstrated that vibrotactile feedback could provide users with sufficient proprioceptive information that allowed them to perform position sense and kinesthesia recognition. Four experimental blocks tested the subject’s ability to recognize varying aspects of proprioception through encoded vibratory stimuli. The findings suggest that the encoding strategies were highly informative, as shown by the high success rates following minimum training, indicating that they could potentially be employed to provide feedback to individuals with sensory deficiencies. This process could be employed for different future applications, which include improving the use of assistive or teleoperated devices, and assisting in sensory rehabilitation of clinical populations with sensory deficits.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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11
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