WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues

Heather Culbertson **Julie M. Walker** **Michael Raitor** **Allison M. Okamura**
Department of Mechanical Engineering
Stanford University
{hculbert, jwalker4, mraitor, aokamura}@stanford.edu

ABSTRACT

WAVES, a Wearable Asymmetric Vibration Excitation System, is a novel wearable haptic device for presenting three dimensions of translation and rotation guidance cues. In contrast to traditional vibration feedback, which usually requires that users learn to interpret a binary cue, asymmetric vibrations have been shown to induce a pulling sensation in a desired direction. When attached to the fingers, a single voicecoil actuator presents a translation guidance cue and a pair of voicecoil actuators presents a rotation guidance cue. The directionality of mechanoreceptors in the skin led to our choice of the location and orientation of the actuators in order to elicit very strong sensations in certain directions. For example, users distinguished a "left" cue versus a "right" cue 94.5% of the time. When presented with one of six possible direction cues, users on average correctly identified the direction of translation cues 86.1% of the time and rotation cues 69.0% of the time.

ACM Classification Keywords

H.5.2 [Information Interfaces and Presentation]: User Interfaces - Haptic I/O; H.1.2 [Models and Principles]: User/Machine Systems - Human Factors

Author Keywords

Haptics; vibration; haptic guidance; wearable devices

INTRODUCTION

Humans depend heavily on visual information to guide their motion in both large scale navigation through an environment and smaller scale motor tasks. However, there are tasks during which a user's visual attention is needed elsewhere, such as when a pedestrian navigates around a city by GPS. By leveraging the sense of touch to replace visual guidance with haptic guidance cues, we can free visual attention for other purposes.

This mapping of visual information to the sense of touch, however, is difficult due to the limited degrees of freedom available. Collins created a system for displaying a visual scene to the back of a blind individual using a 20×20 array of solenoids, which has 1/10 the resolution of the human eye [12]. Arrays of haptic actuators this size are not practical for everyday use, especially in portable applications. Guidance information is less complex than a full image, but the degrees of freedom of haptic actuation can be very limited compared to vision – typically, haptic guidance systems require at least one actuator per direction. This one-to-one mapping quickly limits the complexity of guidance cues that can be displayed. The system we present in this paper requires only six actuators to display twelve distinct direction cues, a marked improvement over traditional haptic feedback methods.

A haptic guidance system's usability also depends on the method and location of attachment to the skin. The haptic sensations must be easily sensed, so the actuators should be located on a part of the body with a high density of mechanoreceptors. The guidance system should also be unobtrusive and should not drastically hinder everyday activities. Although hands have high densities of mechanoreceptors [21], holdable guidance devices are not ideal because they monopolize the use of that hand. In contrast, our system directly attaches the actuators to the fingertips. This allows us to leverage the high sensitivity of the fingertips that is due to the large number of mechanoreceptors, and additionally the actuators are small and allow the hand freedom of motion.

Haptic guidance has been shown to be effective in tasks where cognitive load is high [31]. In order to alleviate some of the cognitive load, the haptic guidance cues must be easy to recognize and interpret. However, many traditional haptic guidance systems rely on patterned or sequential activation of multiple actuators [23][27]. These patterns can be difficult to decipher due to the close activation in location and/or time of multiple actuators [10]. Our system creates intuitive pulling and twisting sensations that compel users to move in the desired direction, rather than requiring users to interpret arbitrary cues.

In this paper, we present a wearable haptic device that can provide three-degree-of-freedom guidance through the use of asymmetric vibrations. It can provide either translation or rotation cues to a user's hands for navigation. Future uses of the device include guidance for body pose during rehabilitation and training. We show that users can identify both translation and rotation directions, and we discuss the perceptual concepts that affect the ability of wearers to perceive asymmetric vibrations.

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RELATED WORK

Vibration Guidance

Much of the prior work in haptic guidance has focused on vibration because it is cheap, lightweight, and easily scalable. Simple symmetric vibrations are capable of communicating information to the user about their current or desired state in navigational or other guidance tasks. However, these high-frequency (typically 100-250 Hz) vibrations are limited by adaptation of the skin through prolonged use [17] and difficulty localizing individual vibration tactors [22]. Furthermore, since most vibration actuators provide only a binary cue (on or off) a separate actuator is required for each direction.

Vibration feedback has been used successfully in pedestrian navigation using holdable devices [26][28]. Rather than providing constant vibration feedback, these systems only provided information if the user had to make a choice of direction. More commonly, vibration navigation systems are wearable, although they vary in size, complexity, and form factor. Ertan et al. created a vest with an array of vibration motors to display navigation direction cues [14]. The direction cues were displayed by sequentially activating the actuators in a different pattern for each cue. Previous wearable haptic navigation systems have also used vibration actuators in devices worn on the wrist, waist, ankle, and foot [23][36]. Although wearable vibrotactile navigation cues are very versatile, they often rely on users to interpret a patterned cue before acting on it.

Vibrations have also been used to provide feedback to assist users in completing a task, including following a specified arm trajectory [5] or completing a needle insertion task [27]. These systems rely on the use of multiple actuators to display cues. The user must then discern the order in which the vibrations activate, localize the vibrations to a point on the body, and decode the pattern, which creates a large cognitive load and can lead to errors.

Skin Deformation Guidance

Many researchers have also explored the use of skin deformation to provide directional guidance cues. Gleeson et al. used a tactor to apply shear forces to the fingertip to display four directions of guidance cues [15]. This system was expanded to display five-degree-of-freedom directional cues (two translation and three rotation) using two separate two degree-of-freedom tactors [16]. Schorr et al. used skin deformation to provide feedback about the user's error when following a path [29]. The users were able to easily perceive and interpret the skin deformation feedback, although they had larger errors than with force feedback due to a delay between receiving and acting on the feedback signal. This delay resulted from the time it took users to process the meaning of the feedback signal.

Other Haptic Guidance

To avoid the limitations of vibration and skin stretch, other novel haptic modalities have also been explored for use in guidance tasks. Spiers et al. created a shape-changing haptic device to display pedestrian navigation cues [32]. This shape-changing device was preferred over a vibrotactile device because it was easier to interpret the cues and the sensations were more comfortable. Nakamura et al. created directional heading cues through the Hanger Reflex by applying torqued skin deformation around the wrist or waist using an elliptical cast [24]. He et al. created a device that uses pneumatics to provide directional cues [18]. This device was capable of providing salient direction cues, but was slow to activate.

Asymmetric Vibrations

Recently, researchers have explored a method of using vibration to create guidance cues that are more intuitive than previous vibration feedback methods. Asymmetric vibrations, which are characterized by large positive acceleration peaks and small negative acceleration peaks, provide a compelling sensation of being pulled in the direction of the large acceleration. This sensation is in stark contrast to the simple binary cues presented by standard vibration feedback. It eliminates the interpretation step required for binary vibration cues and can present two directions with one vibration actuator.

Asymmetric vibrations are generated by accelerating a mass along a linear path with unequal speeds in the two directions. Amemiya et al. built the first asymmetric vibration system, which uses a slider-crank to elicit a pulling sensation [1],[2]. Shima and Takemura created an ungrounded device that could present a similar pulling sensation using a mass attached to a spring [30]. Pulling sensations have also been successfully generated by asymmetrically controlling the speed and direction of a handle [34] and a pivoting plate [19]. Although these systems produced salient pulling sensations, their size and mass limit their applicability to mobile haptic systems.

Several researchers have expanded the initial work in asymmetric vibrations to produce similar pulling sensations using small linear vibration actuators. The principles behind this approach are the same: a mass (a magnet) inside the actuator is accelerated faster in one direction than another. Rekimoto created a system using a linear resonant actuator with asymmetrically-timed current pulses [25]. Amemiya and Gomi designed a similar system using a voicecoil actuator [3]. They compared their system and the one developed by Rekimoto, and they found that their system produced stronger pulling sensations in both directions. Tanabe et al. generated asymmetric vibrations using a speaker-type vibration actuator [33]. Building on the success of these initial prototypes, Culbertson et al. modeled and analyzed the mechanism behind the creation of the pulling sensation from asymmetric vibrations and determined that the sensation is caused by asymmetric skin displacement [13].

This paper presents the design and analysis of WAVES, a Wearable Asymmetric Vibration Excitation System for displaying three-dimensional translation or three-dimensional rotation cues. The system avoids many of the inherent limitations of holdable devices, such as requiring specific hand positions and constraining the motion of the hand, by directly attaching the actuators to the hand. Building on the success of previous asymmetric vibration systems, WAVES provides intuitive direction cues by creating salient pulling and twisting sensations.

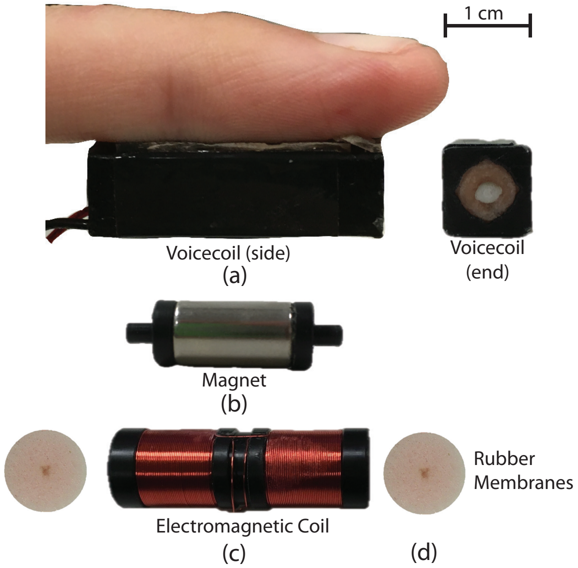

Figure 1. (a) Voicecoil actuator used to create the asymmetric vibrations. The actuator includes a (b) permanent magnet suspended inside of an (c) electromagetic coil. (d) Rubber flexure membranes keep the magnet centered and determine the frequency characteristics of the actuator.

CREATING ASYMMETRIC VIBRATIONS

This section presents our methods for creating an ungrounded pulling or twisting sensation using a voicecoil actuator that is vibrated asymmetrically.

Hardware

We generate asymmetric vibrations using a Haptuator Mark II voicecoil actuator (Tactile Labs). We chose this actuator for its low mass (9.5 grams), small size ($9 \times 9 \times 32$ mm), and frequency characteristics ($f_{\text{res}} \approx 110$ Hz). The Haptuator includes a permanent magnet suspended inside an electromagnetic coil between two flexure membranes, as shown in Fig. 1.

The asymmetric vibrations are generated by moving the magnet unevenly along the axis of the actuator. The model presented in [13] determined that an optimum signal to drive the voicecoil actuators to create a salient pulling sensation is the step-ramp current pulse shown in Fig. 2. The step portion of the signal pushes the magnet quickly in one direction, creating a large force pulse. The ramp portion of the current pulse then slowly returns the magnet to its starting position, creating a smaller force that occurs over a longer period of time.

The commanded current signal is scaled and converted to a voltage before being output at 1000 Hz through an analog output pin on a Sensoray 826 PCI card. The output voltage is then passed through a custom-built linear current amplifier using a power op-amp (LM675T) with a gain of 0.5 A/V.

Perception

Although the net force over the duration of a cycle is zero, the difference in magnitude between the force pulses during the step and the return of the magnet causes a net pulling sensation in the direction of the larger force pulse. When the actuator is held in contact with a person's skin, the force pulses deform the skin. The faster skin deformation due to the step is sensed more strongly than the slower skin deformation of the return [15], intensifying the perception of the pulling.

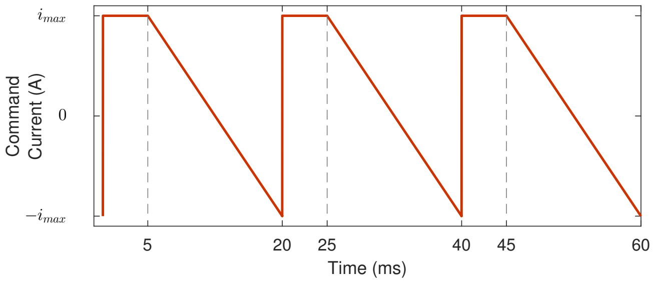

Figure 2. The commanded current pulses used to drive a voicecoil actuator to create asymmetric vibrations. The direction of the asymmetric vibrations can be switched by inverting the current signal.

The timing of the current pulse is tuned to maximize the strength of the pulling sensation by optimizing the ratios of positive to negative peak skin displacements and skin displacement speeds. For the actuator used in this paper, we determined the optimal timing to be $t_{\text{step}} = 5$ ms, $t_{\text{ramp}} = 15$ ms. These asymmetric vibrations at 50 Hz are sensed by both the Meissner corpuscles, which are sensitive to dynamic skin deformation, and the Pacinian corpuscles, which are sensitive to high-frequency vibrations [22]. However, the Pacinian corpuscles do not sense the direction of the vibrations [6], so only the Meissner corpuscles are responsible for the pulling sensation induced by the asymmetric vibrations. The magnitude of the skin deformation (≈ 0.25 mm [13]) is well above the detection threshold determined in [20].

The strength of the perceived pulling sensation is not a constant force, and has been shown to increase when the user moves their limb [4]. This is contrary to traditional vibration feedback systems, in which the accuracy of the cue is diminished due to motion [23]. This phenomena of increased perception with motion deserves further study.

Twisting sensations are created by playing asymmetric vibrations in opposite directions and in slightly offset locations on the body. The actuators must be parallel to one another so that the pulling sensations create a perceived force couple. They must be positioned close enough that the sensation from the two actuators is perceived as coming from the same area of skin, but also be far enough apart so that the receptive fields of the Meissner corpuscles stimulated by each actuator do not overlap. Furthermore, the actuators must be timed so that the force peaks occur at the same time or the overall sensation will be diminished.

WEARABLE SYSTEM

Previous asymmetric vibration systems were holdable [3][25][33]. Here we describe our methods for creating compelling wearable systems, which have three degrees of freedom – more than any previous holdable system.

Mounting Locations

In order to induce a strong pulling or twisting sensation, we chose mounting locations that maximized the number of

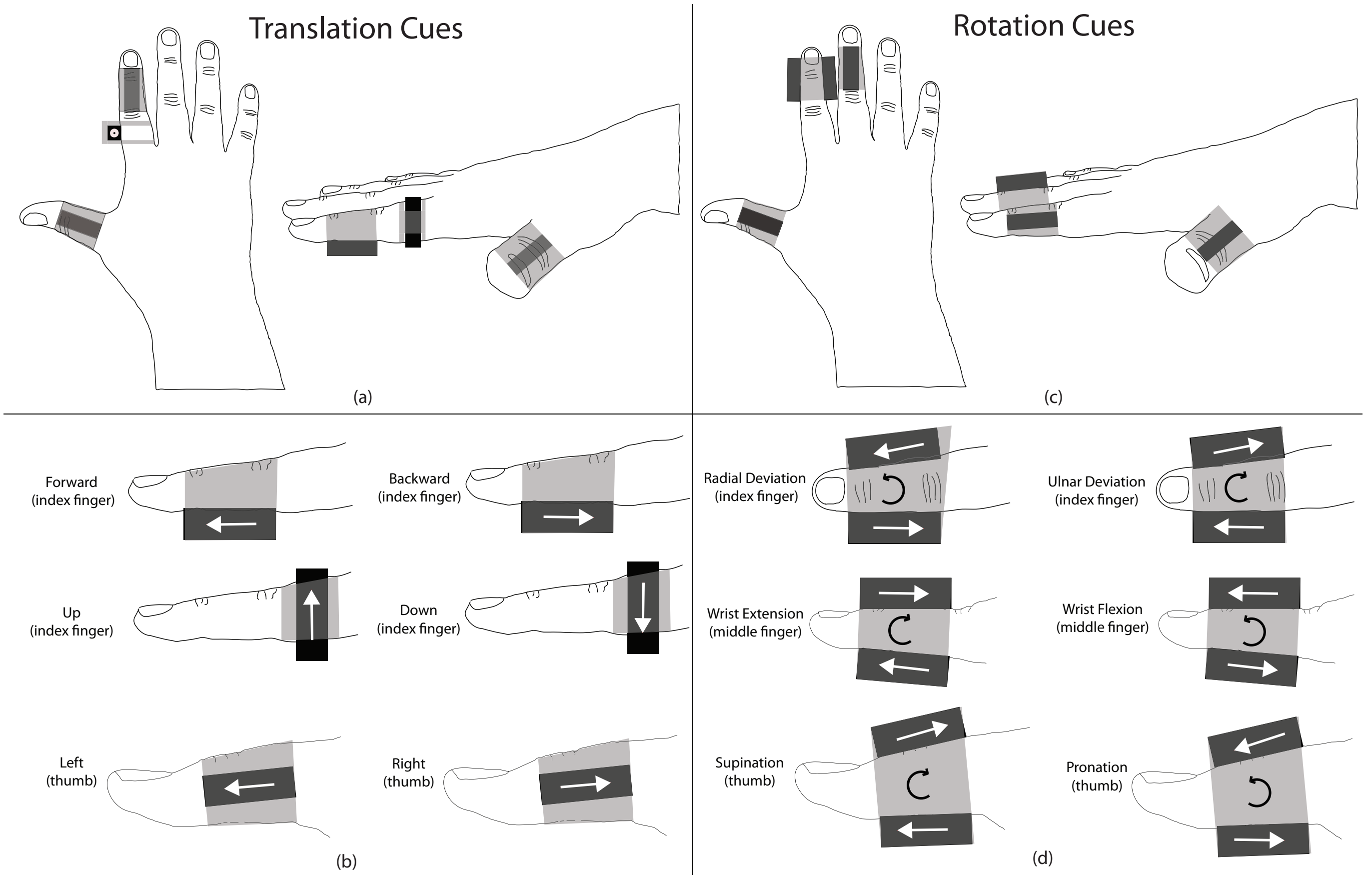

Figure 3. (a) Configuration of actuators on hand to display translation cues. (b) The actuator on the thumb displays left-right cues, the actuator on the bottom of index finger displays forward-backward cues, and the actuators on the left of the index finger displays the up-down cues. (c) Configuration of actuators on hand to display rotational cues. (d) Actuators on the index finger display radial-ulnar deviation cues, actuators on the middle finger display extension-flexion cues, and actuators on the thumb display supination-pronation cues.

mechanoreceptors stimulated. As discussed earlier, asymmetric vibrations are sensed by the Meissner Corpuscles. Johansson and Vallbo determined that the human hand has significantly higher concentration of Meissner Corpuscles along the radial nerve and on the distal end of the thumb, index, and middle fingers [21]. Therefore, in creating our wearable device, we focused on these areas for actuator placement.

Humans are more sensitive to tangential skin displacement than normal skin displacement [7]. Therefore, to maximize the pulling sensation, the actuators must be placed so that they displace the skin tangentially. The optimal actuator placement is different for displaying translation or rotation cues.

Translations

The density of mechanoreceptors is higher on the fingers than the rest of the hand. Our pilot investigations of actuator placement confirmed that the pulling sensation was strongest when the actuators were attached to the fingers. Creating a system capable of providing cues for multiple degrees of translation required us to place actuators on multiple fingers.

As discussed above, the vibrations are transmitted most completely from the actuator to the skin when the contact between actuator and skin is maximized. To display cues for three orthogonal directions, we added actuators to the side of the thumb, and the bottom and side of the index finger, as shown in Fig. 3. The thumb is held out at an approximately right angle to the rest of the fingers and is used to display the left-right cues. A second actuator is attached to the bottom of the index finger and is used to display the forward-backward cues. These two actuators are attached using elastic straps. A third actuator is attached to the side of the index finger using a silicone sleeve and is used to display the up-down cues. A piece of Very High Bond (VHB, 3M) tape further secures this actuator to the finger to increase the skin deformation and ensure that the actuator does not slip against the skin.

Rotations

Twisting sensations are created using pairs of parallel actuators on opposite sides of the fingers that display asymmetric vibrations in opposing directions. Rather than simply doubling the actuators on the translation configuration, we must optimally choose mounting locations specifically with rotations in mind. Our system is capable of displaying six directions of wrist rotation cues: radial deviation, ulnar deviation, wrist extension, wrist flexion, supination, and pronation. Six actuators are attached to the thumb, index finger, and middle finger of the right hand, as shown in Fig. 3.

Two actuators are attached to the left and right of the index finger to display radial-ulnar deviation cues. When the left actuator is pulsed proximally and the right actuator is pulsed distally, the finger feels a counter-clockwise twisting sensation, which signals radial deviation. When the left actuator is pulsed distally and the right actuator is pulsed proximally, the finger feels a clockwise twisting sensation, which signals ulnar deviation.

Two actuators are attached on the top and bottom of the middle finger to display wrist extension-flexion cues. When the top actuator is pulsed proximally and the bottom actuator is pulsed distally, the finger feels an upwards tilting sensation, which signals extension. When the top actuator is pulsed distally and the bottom actuator is pulsed proximally, the finger feels a downwards tilting sensation, which signals flexion.

Two actuators are attached to the top and bottom of the thumb to display the supination-pronation cues. When the top actuator is pulsed proximally and the bottom actuator is pulsed distally, the thumb feels an upwards tilting sensation, which signals supination. When the top actuator is pulsed distally and the bottom actuator is pulsed proximally, the thumb feels a downwards tilting sensation, which signals pronation.

Mounting Methods

The materials used for mounting the actuators to the hand must be lightweight because the amount of skin deformation is dependent on the mass that the actuator must move [13]. Furthermore, the vibrations must maintain their commanded shape and direction when transmitted to the skin. Rigid components were tested as part of the mounting hardware, but they distorted and spread out the vibrations in multiple directions, causing the user to feel simple vibration rather than pulling or twisting. Instead, we found that soft materials such as fabric and silicone perform better at maintaining vibration directionality and were better choices for attaching the actuators.

The amount of skin displacement depends on the stiffness and damping properties of the skin. The damping of the skin increases with increasing normal force, which leads to decreased skin displacement overall. Therefore, the actuators should not be too tightly coupled to the hand. However, sufficient normal force is needed to ensure that the actuator remains in contact with the skin so that vibrations can be transmitted properly.

In our design, elastic straps were used to attach the actuators to the hand. The straps were the same width as the actuator to ensure that the normal force was evenly spread over the length of the actuator and all points on the surface of the actuator were in contact with the skin. The elastic straps did not stretch in the direction of actuation, so all force from the actuator was transmitted to skin deformation. The tightness of the straps were chosen so that the actuator maintained contact with the skin, but did not cause discomfort. A silicone sleeve was used to attach one of the actuators mounted normal to the side of the finger, as shown in the Up and Down (index finger) cases in Fig. 3(b), in order to increase the amount of skin deformation. The silicone damped out vibration too much for actuators mounted tangential to the finger.

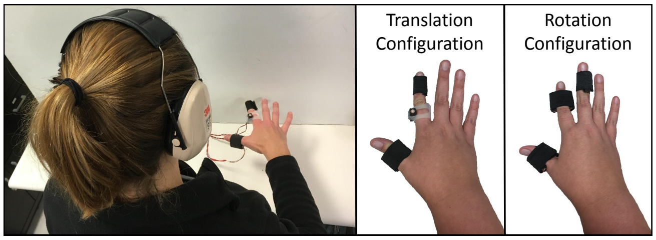

Figure 4. Experimental setup. Participants sat at a table and wore the actuators on their right hand. Noise canceling headphones blocked auditory cues from the actuators.

EXPERIMENTAL METHODS

We tested the effectiveness of our device at displaying rotation and translation cues through a user study. We recruited 12 right-handed participants (7 male, 5 female, 23-42 years old). Six of the participants had prior experience with haptic devices. The protocol was approved by the Stanford University Institutional Review Board (Protocol Number 22514), and all participants gave informed consent.

Experiment Set-Up

Participants sat at a table with the actuators attached to their right hand, as shown in Fig. 4. They wore noise-canceling headphones so they could not use auditory cues, and they closed their eyes so they could not use visual cues to distinguish the directions. During the study, participants held their hand in front of their body and above the table with their palm faced downward. Participants began each trial with their hand held in the same neutral position, but were allowed to move their hand during the trial.

Experimental Procedure

Participants identified translation and rotation cues in two separate experiment blocks. Both blocks followed a forced-choice paradigm where participants received a cue and responded with one of six possible directions. Before each block, participants were trained on the different direction cues. They were first allowed to feel all six directions shown in Fig. 3 until they felt comfortable with their ability to identify the cues.

> translation block: left, right, forward, backward, up, down
>
> rotation block: radial deviation, ulnar deviation, extension, flexion, pronation, supination

Since the strength of the pulling or twisting sensation is dependent on actuator placement, adjustments to actuator location and orientation were made as needed until the sensation was maximized. Next, participants received further training by completing 18 practice trials (3 trials for each condition) and received feedback about whether they had responded correctly. After training, participants completed 72 pseudorandom experimental trials (12 trials for each condition). For each trial, a 3-second-long cue was played, and participants were allowed to feel each cue up to three times before answering. Participants verbalized their answer, and the experimenter input the response into the computer. Participants were randomly assigned the order of the experimental blocks, with half of the participants completing the translation block first.

The participants rested for five minutes between the two experimental blocks to allow them to recover from any vibration adaptation that had occurred. Recovery from vibration adaptation takes approximately half as long as the length of the original vibration signal [17]. Since two actuators were used for the rotation directions, the amplitude of the input current was scaled down so that the combined maximum current sent to both actuators matched the maximum current sent to the single actuator in the translation portion of the experiment. This scaling meant that the vibrations used to display the translation and rotation cues were the same strength.

Analysis

We created separate linear mixed effects models for the translation and rotation participant response data. The six directions are treated as separate fixed effects and participant as a random effect. We assume a binomial distribution for the responses, which uses the link function:

$$y = \log\left(\frac{\mu}{1-\mu}\right) \tag{1}$$

where μ is the proportion of correct responses. The linear model takes the form:

$$y = \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + bS + \varepsilon \tag{2}$$

where β_n is the fixed effect parameter to model the effect of the n_{th} direction X_n, b is a random effects parameter to model the differences across participants S, and ε is the residual error [11]. Statistical significance was determined using a maximum likelihood test.

The model given in Eq. (2) depends independently on the directions, which are mutually exclusive. The regression in the model examines the change in the likelihood that the response is correct given that more trials are run for a given direction. Therefore, each fixed effect coefficient is a measurement of the estimated increase in the proportion of total correct trials if a new trial is run for a given direction.

RESULTS

Translation

The percentage of correct responses was calculated separately for each participant and condition (Fig. 5). The percentages of responses for each condition were then averaged across participants. The resulting confusion matrix of the participants' responses for the translation directions is shown in Table 1. Participants only ever confused a direction cue with its counterpart (i.e. right was only ever confused with left).

The results of the linear mixed model for the translation responses are shown in Table 2. All directions had positive coefficients, which indicated that the probability of a correct answer would increase with more trials of a given condition. Furthermore, the odds of selecting the correct response (average 86.1%) was significantly greater than chance (16.7%) for all six translation directions ($p < 0.05$).

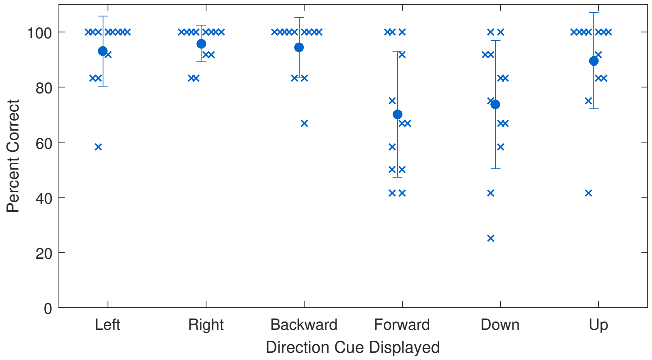

Figure 5. Percent correct for translation experiment. Filled circles indicate average of all participants, and lines show standard deviation. ×'s indicate proportion correct for individual participants.

	Correct Direction					
Response	Left	Right	Back	Forward	Down	Up
Left	93.1	4.2	0.0	0.0	0.0	0.0
Right	6.9	95.8	0.0	0.0	0.0	0.0
Backward	0.0	0.0	94.4	29.9	0.0	0.0
Forward	0.0	0.0	5.6	70.1	0.0	0.0
Down	0.0	0.0	0.0	0.0	73.6	10.4
Up	0.0	0.0	0.0	0.0	26.4	89.6

Table 1. Confusion table showing user responses for each translation direction. Cells are shaded according to percentage.

In the linear mixed model, participant was treated as a random effect. Not all participants performed equally well. Two participants had statistically lower accuracies than average ($b = -0.970$, $t(858) = -2.81$, $p = 0.005$), ($b = -0.818$, $t(858) = -2.34$, $p = 0.020$). One participant had a statistically higher accuracy than average ($b = 1.436$, $t(858) = 2.83$, $p = 0.005$). These differences are partially due to variations in finger size and geometry, as will be discussed in later sections.

All participants commented that they felt one direction out of a pair more strongly than the other: right cues felt more salient than left cues, backward cues felt more salient than forward cues, and up cues felt more salient than down cues. This perceived discrepancy is mirrored in the percentage correct shown in Fig. 5. We performed a repeated measures ANOVA with participant as the independent variable and direction as the within-subjects factor for each pair of directions to determine systematic variations in the accuracies across the directions. Right had a higher percentage of correct answers (mean 95.8%, SD 6.6%) than left (mean 93.1%, SD 12.7%) ($F(1,10) = 0.216$, $p = 0.65$), backward had a higher percentage correct (mean 94.4%, SD 10.9%) than forward (mean 70.1%, SD 22.9%) ($F(1,10) = 9.82$, $p = 0.011$), and up had a higher percentage correct (mean 89.6%, SD 17.5%) than down (mean 73.6%, SD 23.3%) ($F(1,10) = 3.84$, $p = 0.077$).

	Fixed Effect	t(858)	p-value
Left	2.763	6.93	8.21×10^{-12}
Right	1.656	6.97	6.16×10^{-12}
Backward	1.002	7.01	4.89×10^{-12}
Forward	0.236	3.27	1.12×10^{-3}
Down	0.225	3.84	1.30×10^{-4}
Up	0.385	6.51	1.26×10^{-10}

Table 2. Results of fitting linear fixed effects model to translation responses.

The increased strength of the pulling sensation in the right and backward directions over the left and forward directions can at least partially be explained by the actuator placement. Both the right and backward cues were displayed with larger proximal force pulses, whereas the left and forward cues were displayed with larger distal force pulses. The Meissner corpuscles respond more strongly to proximal stimuli than distal stimuli [8], making proximal signals feel stronger. This nonuniformity in the strength of the signals is also apparent in the larger percentage correct for right than for left and larger percentage correct for backward than for forward. The high percentage for the left cue is due to the overall strength of the right cue; many participants indicated that the left cue was felt weakly, but the right cue was so strong and easily discernible that any cue felt on the thumb that was not right had to be left. The nonuniformity in the perceived strength of the proximal and distal cues could be corrected by amplifying the distal signals so both directions are perceived as the same strength.

The up and down cues had slightly lower accuracies than the other cues, although this difference was not statistically significant. One potential cause of this lower overall accuracy is that the actuator for the up/down cues was mounted to the side of the index finger, which meant less contact between the actuator and the skin and resulted in less efficient transfer of vibration to the finger. The sensations in the up/down directions were also affected by gravity. When the force pulses from the actuator are oriented with gravity, they are felt as slightly stronger because they are assisted by gravity. However, when the force pulses are oriented opposing gravity, they are felt as weaker because they have to work against gravity. Furthermore, the elasticity of the silicone sleeve that attached the actuator to the finger inverted the direction of the force pulses applied to the finger. Since the silicone sleeve was easier to stretch than the skin, the force pulses from the actuator displaced the band in the direction of the pulses and the opposite reaction force pulses would be felt by the finger. Therefore, when the actuator's force pulses were oriented downwards, the user felt an up cue and when the actuator's force pulses were oriented upwards, the user felt a down cue. Thus, combined with the effect of gravity, the up cues felt stronger than the down cues. This is supported by the higher percentage correct for the down cues than the up cues, and was confirmed by all participants who stated that the up cue was easier to determine.

Participants were also asked to rate the difficulty of distinguishing the pairs of translation cues from one another on a five-point Likert scale, with 1 being "very easy" and 5 being "very hard" to distinguish. Participants rated the task of distinguishing left and right (mean = 2.18) as being significantly easier ($p = 0.018$) than the task of distinguishing up and down (mean = 3.45). The task of distinguishing backward and forward was not rated as significantly harder or easier than the other pairs (mean = 2.77, $p > 0.25$)

All participants reported feeling a pulling sensation in the direction of actuation, and many were observed to move their hand to help determine the cue direction. They reported feeling an assisting force when moving hand in the direction of the cue, and a resisting force when moving opposite the direction of the cue. We chose to display a relatively lengthy 3-second-long cue to give the participants time to move before responding.

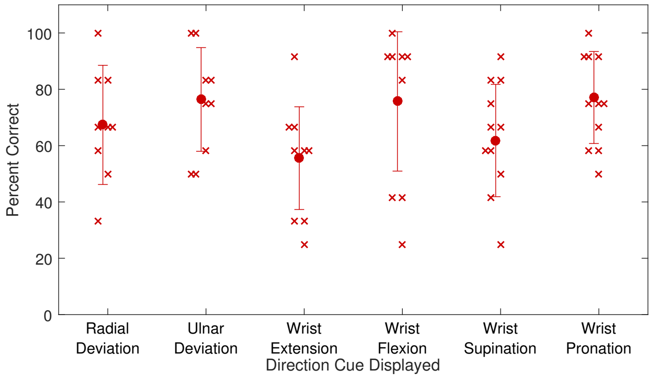

Figure 6. Percent correct for rotation experiment. Filled circles indicate average of all participants, and lines show standard deviation. ×'s indicate proportion correct for individual participants.

	Correct Direction					
Response	Radial	Ulnar	Ext.	Flex.	Sup.	Pron.
Radial	67.4	23.6	0.0	0.0	0.0	0.0
Ulnar	32.6	76.4	0.0	0.0	0.0	0.0
Ext.	0.0	0.0	55.6	24.3	0.0	0.0
Flex.	0.0	0.0	44.4	75.7	0.0	0.0
Sup.	0.0	0.0	0.0	0.0	61.8	22.9
Pron.	0.0	0.0	0.0	0.0	38.2	77.1

Table 3. Confusion table showing user responses for each rotation direction. Cells are shaded according to percentage.

Rotation

The percentage of correct responses was calculated separately for each participant and condition (Fig. 6). The percentages of responses for each condition were then averaged across participants. The resulting confusion matrix of the participants' responses for the rotation directions is shown in Table 3. As in the translation study, participants only ever confused a direction cue with its counterpart (i.e. radial deviation was only ever confused with ulnar deviation).

The results of the linear mixed model for the rotation responses are shown in Table 4. All directions had positive coefficients, indicating that the probability of a correct answer would increase with more trials of a given condition. Furthermore, the odds of a correct response was significantly greater than chance for five of the six rotation directions (radial deviation, ulnar deviation, flexion, pronation, and supination) ($p < 0.05$).

	Fixed Effect	t(858)	p-value
Radial	0.749	3.38	7.64×10^{-4}
Ulnar	0.606	5.11	3.95×10^{-7}
Extension	0.077	1.08	0.281
Flexion	0.293	4.98	7.68×10^{-7}
Supination	0.100	2.30	0.022
Pronation	0.209	5.24	2.00×10^{-7}

Table 4. Results of fitting linear fixed effects model to rotation responses.

In the linear mixed model, participants were treated as random effects. Not all participants performed equally well. Two participants had statistically lower accuracies than average ($b = -0.572$, $t(858) = -2.36$, $p = 0.019$), ($b = -0.617$, $t(858) = -2.55$, $p = 0.011$). One participant had a statistically higher accuracy than average ($b = 0.609$, $t(858) = 2.26$, $p = 0.024$).

The participants' ability to discriminate the rotation directions was correlated with their finger size. We measured the circumference of the second phalange of the index finger, middle finger, and thumb. We then binned the participants into two pools based on their average circumference of those three fingers: participants with average finger circumference less than 60 mm (5 participants) and participants with average finger circumference greater than 60 mm (7 participants). We then performed a repeated measures ANOVA on the percentage correct with condition as the independent variable and finger size (small or large) as the within-subjects factor. Participants with smaller fingers had statistically lower accuracies than participants with larger fingers at the rotation experiment ($F(1,28) = 11.23$, $p = 0.002$). Analyzing the response data for only the participants with larger fingers, the accuracy improves drastically for the radial (81.0%), ulnar (83.3%), and flexion (88.1%) directions. The accuracy improves slightly for the extension (57.1%), supination (63.0%), and pronation (78.6%) directions. There were no statistical differences in the translation experiment for participants with small and large fingers. For our participants, finger size was correlated to gender; four female participants fell in the smaller finger category versus one female participant in the larger finger category.

During the experiment, all participants reported feeling wrist flexion cues more strongly than wrist extension cues. Many participants also reported feeling wrist pronation cues more strongly that wrist supination cues. We performed a repeated measures ANOVA with participant as the independent variable and direction as the within-subjects factor for each pair of conditions. Ulnar deviation had a higher percentage correct (mean 76.4%, SD 18.4%) than radial deviation (mean 67.4%, SD 21.1%) ($F(1,10) = 0.004$, $p = 0.95$), wrist flexion had a higher percentage correct (mean 75.7%, SD 24.7%) than wrist extension (mean 55.6%, SD 18.2%) ($F(1,10) = 2.12$, $p = 0.18$), and pronation had a higher percentage correct (mean 77.1%, SD 16.3%) than supination (mean 61.8%, SD 19.9%) ($F(1,10) = 0.445$, $p = 0.063$).

Participants were asked to rate the difficulty of distinguishing the pairs of rotation cues from one another on a five-point Likert scale, with 1 being "very easy" and 5 being "very hard" to distinguish. Participants rated the task of distinguishing radial and ulnar deviation (mean=3.09) as being significantly easier ($p = 0.029$) than the task of distinguishing flexion and extension (mean=3.77) or pronation and supination (mean=3.77).

Although the differences were not significant, the radial and ulnar extension cues also had the highest combined percentage correct of any of the pairs (71.9%). Actuator placement likely affected why participants found this task easier than the others. The actuators used for radial and ulnar extension were located on the left and right sides of the index finger. The two actuator locations for this cue have the same tactile properties and sensitivity, although directional differences may still occur.

Conversely, the cues for wrist flexion-extension and pronation-supination were displayed on the dorsal side and the palmar side of the finger. Vibrations are sensed differently on these two sides of the finger due to the presence of the finger bones closer to the surface on the dorsal side of the finger and the layers of fatty tissue on the palmar side of the finger [35]. The mounting location on the dorsal side of the finger is more rigid due to the bone, which causes the vibrations to spread out and become difficult to localize. Conversely, on the palmar side of the finger, the thick layers of fatty tissue allow the force pulses to displace the skin in the desired profile with less noise. Furthermore, the actuators on the dorsal side were placed on hairy skin and the actuators on the palmar side were placed on glabrous skin. The actuators on glabrous skin were sensed more strongly than actuators on hairy skin due to the unequal sensitivity of the mechanoreceptors in the two types of skin [9], which was confirmed by many participants. Therefore, the asymmetric vibrations displayed on the palmar side of the finger created more salient pulling sensations than on the dorsal side of the finger. This could have significantly degraded the torque sensation for those cues, or resulted in torque pairs that felt stronger in one direction than the other, which is evident in the results of the study.

The only rotation condition that was not identified significantly higher than chance was wrist extension. Participants also consistently reported this as the most difficult direction to feel. The wrist extension cue was displayed with distal force pulses on the bottom of the finger and proximal pulses on the top of the finger, as shown in Fig. 3. In the translation experiment, the forward cue displayed distally on the bottom of the finger was the most difficult to distinguish due to the lower distal activation of the Meissner corpuscles. Thus, the portion of the wrist extension cue on the bottom of the finger was likely perceived more weakly than expected. This was further compounded by the cue on the top of the finger that was weaker due to the lower sensitivity of hairy skin.

All participants reported feeling a twisting sensation in the direction of actuation. Similar to the translation experiment, many participants reported rotating their hand to help them determine which direction the cue was telling them to move.

DISCUSSION

Translation

Traditional vibration guidance systems use high-frequency vibrations that excite the Pacinian Corpuscles [23][27]. However, Pacinian Corpuscles have large receptive fields, making it difficult to localize the vibration [22]. Our WAVES device, on the other hand, vibrates at a lower frequency, which excites the Meissner Corpuscles. These mechanoreceptors have much smaller receptive fields, making it significantly easier for users to localize the vibration. Furthermore, our system requires only one actuator per degree of freedom and is easy to scale to multiple dimensions; traditional vibration feedback systems usually requires at least two actuators per degree of freedom, which limits the number of degrees due to spatial sensitivity.

The ease with which participants were able to determine the location of the vibrations can be seen in the confusion matrix; no directions were confused except with their counterpart. The ability to localize the vibration to the individual fingers combined with the salient pulling sensations from the actuators means that the chance of choosing a correct answer becomes 50% since they were able to immediately narrow their choices to a pair of directions. This higher initial probability is a significant improvement over past vibration guidance systems. Participants responded correctly with significantly higher accuracy than chance for all translation directions. The consistently high accuracies for four of the directions (left, right, backward, up) indicate that the participants were able to feel salient pulling sensations in these directions. Our system shows significantly higher accuracy displaying six directions than the multiple direction asymmetric vibration device presented in [25]. This improved performance shows promise for our system that isolates the actuators from each other, making the cues easier to recognize and interpret.

Ideally, all participants would have had similar accuracy identifying directions. However, two participants had statistically poorer performance for the translation cues than the other participants. This discrepancy indicates that the training might not have been sufficient for all participants. It is possible that with more training, all participants would have been able to perform at the same level. Additional training may have also increased the recognition rates of all participants. The accuracies may have been affected by desensitization to vibration, which could be mitigated with more breaks between trials. Desensitization and adaption to the vibrations may limit the real-world applicability of our device; our system would be most effective for tasks where guidance or feedback is needed only intermittently. Variation in actuator placement may also explain some differences between participants. Since the pulling sensation is dependent on skin displacement and excitation of the Meissner corpuscles, the placement of the actuators is very important. Finger size and shape varied widely across participants, so it was not possible to get perfectly consistent actuator placement. A better and more consistent method for attaching actuators to the fingers should be developed in the future.

The results show that the up and down cues were strongly affected by gravity due to the actuator's vertical orientation. In the future, the signals sent to the actuator could be scaled so that the two cues are perceived as the same strength. However, the effect of gravity will change if the user's hand is not in the orientation used in the study, as would be likely in everyday use. Therefore, gravity may play a large role in the perception of the cues as the user moves about the environment. In addition, the inclusion of a distraction task may decrease recognition rates as is seen with traditional vibration devices [27]. However, since the cues presented with our system are intuitive, we expect a smaller decrease in accuracy than for a system with patterned cues.

For everyday use, it would not be ideal for the actuators to be placed on the user's fingertips so that the user's hand could be free to complete other tasks. Therefore, we will explore other mounting locations on the hand such as the sides of the fingers in order to leave the hand more free. We will also explore the addition of coatings to the actuator to increase the amount of skin deformation and remove the need for tape.

Rotation

Although each finger had an actuator on two sides, participants were still able to localize the vibration to an individual finger due to the small receptive fields of the Meissner corpuscles. This localization combined with the noticeable torque sensations allowed participants to easily distinguish between the three pairs of cues by determining which finger the vibration was displayed on. Since no participants confused any of the cues with any other cue except its counterpart, chance for the rotation directions was 50%. Participants responded correctly with significantly higher accuracy than chance for five of the six rotational directions.

Similar to the translation experiment, not all participants performed equally well at the rotation trials. Participants with smaller fingers had statistically lower accuracies than participants with larger fingers. One potential explanation for this discrepancy is that the strength of the torque sensation is dependent on the length of the lever arm between the actuator and the center of rotation in the middle of the finger. This lever arm is shorter for participants with narrower fingers, which would result in smaller torque sensations and could have led to decreased perception and accuracy. The method of attachment could be redesigned to increase the lever arm, effectively increasing the magnitude of the torque sensation, which may lead to increased recognition. For participants with smaller fingers, it is also likely that there was significant vibration interference between the two actuators. In the future, the vibrations strength could be scaled to mitigate this effect.

Another limitation of the torque configurations is the placement of the actuators on the hairy and glabrous skin. Since actuators on glabrous skin were sensed more strongly than actuators on hairy skin, the cues were not as easy to recognize, and some subjects reported feeling a pulling rather than a twisting sensation. In the future, the vibration strength for the two actuators could be scaled so they would be perceived as equal. In addition, mounting locations that do not utilize the hairy skin will be explored. More equal perception between the two actuators for the torque cues will also decrease the confusion between torque cues and simple translation cues, creating the possibility for a single six-degree-of-freedom system.

Applications

Our system was shown to be effective at displaying both translation and rotation guidance cues. In addition to pedestrian navigation, we can apply these capabilities to additional areas of haptic guidance including rehabilitation and sports training. For example, a user whose arm motion is limited by a stroke could wear our system to receive guidance for creating prescribed arm motions during a rehabilitation session from home without the need for external guidance from a therapist. A user could also wear our system to receive real-time feedback for correcting their yoga poses.

Although the studies we presented here were designed to test the system's effectiveness at guiding a user's motion, the system's ability to display salient ungrounded kinesthetic cues opens up several possibilities for use of our device in other scenarios such as haptic virtual reality and teleoperation. The actuators could be used to display forces that result from contacting or moving virtual objects. The system could be especially compelling for use in gaming to display cues through a tool, like those experienced when fighting with a virtual sword.

CONCLUSION

In this paper we describe WAVES, a Wearable Asymmetric Vibration Excitation System for displaying haptic direction guidance cues. Unlike traditional vibration feedback that requires users to interpret a binary cue or match a pattern of vibration, WAVES creates intuitive, easy to interpret direction cues through pulling and twisting sensations. With our approach, only six actuators are necessary to provide twelve distinct direction cues. Users felt compelled to move or rotate their hand in the direction of the guidance cues, and the sensation was amplified by motion with or against the direction of the cue. Actuator placement and contact with the skin was central to creating a salient pulling or twisting sensation. The directional properties of the Meissner Corpuscles created an unequal perception of the directions. Furthermore, the rotation directions were perceived more strongly by participants with larger fingers, partially due to the presence of a larger lever arm creating a larger physical torque. The knowledge we gained in our experiment will guide us in future development of this wearable device.

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