Non-Colocated Kinesthetic Display Limits Compliance Discrimination in the Absence of Terminal Force Cues

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Abstract—An important goal of haptic display is to make available the action/reaction relationships that define interactions between the body and the physical world. While in physical world interactions reaction cues invariably impinge on the same part of the body involved in action (reaction and action are colocated), a haptic interface is quite capable of rendering feedback to a separate body part than that used for producing exploratory actions (non-colocated action and reaction). This most commonly occurs with the use of vibrotactile display, in which a cutaneous cue has been substituted for a kinesthetic cue (a kind of sensory substitution). In this paper, we investigate whether non-colocated force and displacement cues degrade the perception of compliance. Using a custom non-colocated kinesthetic display in which one hand controls displacement and the other senses force, we ask participants to discriminate between two virtual springs with matched terminal force and adjustable non-linearity. An additional condition includes one hand controlling displacement while the other senses force encoded in a vibrotactile cue. Results show that when the terminal force cue is unavailable, and even when sensory substitution is not involved, non-colocated kinesthetic displays degrade compliance discrimination relative to colocated kinesthetic displays. Compliance discrimination is also degraded with vibrotactile display of force. These findings suggest that non-colocated kinesthetic displays and, likewise, cutaneous sensory substitution displays should be avoided when discrimination of compliance is necessary for task success.

Index Terms—Non-colocated force display, colocated force display, vibrotactile display, compliance discrimination, bimanual displays

1 Introduction

When we use our hands to explore the world around us, the principles of active touch are usually in operation. The haptic sensory feedback we receive is produced as a consequence of exploratory actions that we actively and sometimes even deliberately produce. In turn, every object we come in contact with has physical characteristics that dictate invariant relationships between the exploratory motor action and resulting haptic sensory feedback. Haptic perception can be described as the process by which we discern these invariant relationships and compare them to prior experience. This school of thought has been elaborated by many authors including Katz [1], Gibson [2], and O'Regan and Noë [3].

Another important feature regarding this perspective on haptic perception is that we often employ a categorical set of exploratory actions to perceive certain physical characteristics of the environment [4]. When employing such exploratory procedures, we expect the sensory feedback to be delivered in a certain way. In haptic interactions with the physical environment, feedback is perceived by the sensory receptors in the part of the body directly contacting the environment and, possibly, those body parts immediately adjacent or linked to the body part in contact. We do not, for example, run our fingers over a rough surface and feel the resulting vibrations on our back or displace a compliant object with one hand and feel the resulting force on the opposite hand. Rather, the exploratory action and sensory feedback are *colocated* and impinge at a single locus of contact between body and environment.

When our interactions with the environment are mediated through a haptic interface, the exploratory action and resulting feedback can be presented in a *non-colocated* manner. Oftentimes, this is an unintended consequence resulting from other design constraints. In fact, non-colocated displays are quite common in traditional haptic display. This is particularly true when the invariant relationship is intrinsically kinesthetic in nature but the sensory feedback is presented cutaneously to other parts of the body.

An example that is quite common is the vibrotactile display of grip force sensed in an instrumented upper limb prosthesis using a single vibrotactile actuator [5], [6], [7], [8], [9], [10], [11] or an array of vibrotactile actuators [9], [12]. Though in addition to being non-colocated, displaying grip force by modulation of vibration amplitude, vibration frequency, or pattern of activation is a type of sensory

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substitution. The sensory experience elicited by the vibrotactile display must be attributed to interactions between the terminal device and environment and interpreted as grip force. Therefore, to directly investigate how the brain integrates non-colocated kinesthetic action and reaction, the contribution or penalty imposed by sensory substitution should be separately quantified. Nevertheless, our understanding of the manner in which the brain integrates non-colocated action and reaction is quite limited.

In this paper, we aim to quantify the effects on haptic perception of non-colocated action and reaction, that is, placing the point of exploratory action and the point of sensory feedback on different parts of the body. The baseline for comparison is the colocated condition, when the exploratory action and sensory feedback occur at the same point. Further, we aim to assess this effect independent of the effects of sensory substitution. We have chosen the task of compliance discrimination, in which both the exploratory action and resulting feedback are kinesthetic in nature. The compliance of an object that has rigid surfaces is encoded in the relationship between displacement (compression or extension) and force. We exclude additional cues available from a compliant object with non-rigid surfaces [13].

Tan and Durlach [14] conducted seminal work on compliance discrimination using an active pinch grasp of a virtual object with rigid surfaces. Their research concluded that both the terminal force and the mechanical work cue were important for compliance discrimination, and the terminal force cue was sufficient to determine the compliance of objects with linear compliance profiles. They also found that compliance discrimination is poor relative to force and length resolution when the mechanical work cue and terminal force cue were no longer salient. In each of their experiments, participants perceived compliance through a colocated display that derived displacement from and delivered resulting force to the thumb. We then ask the question: Will compliance discrimination be affected by non-colocated force and displacement cues?

While one might expect that displays delivering cues in a non-colocated fashion would certainly lead to degraded perception relative to displays delivering colocated cues, recent work by Dupin et al. [15] suggests that non-colocation does not necessarily lead to degraded perception of object length and orientation. In their work, Dupin et al. investigated the impact of non-colocated kinesthetic and cutaneous action and reaction by developing an experimental paradigm in which the exploratory action of one hand controlled the cutaneous feedback delivered to the other. Performance in the non-colocated task (termed "dissociated task" in Dupin et al.) was found to be no different than performance in the task with colocated kinesthetic and cutaneous cues. Their conclusion was that the brain simplifies the task of multisensory integration by treating the non-colocated cues as if they came from the same hand, thereby preserving haptic perception of object length and orientation. Let us now consider whether the integration of non-colocated force and displacement cues preserves or degrades compliance perception.

We have previously considered non-colocated compliance perception and discrimination in two separate studies. In the first study [16], we considered non-colocated compliance discrimination in an object identification task. The objects in this study were linear leaf springs with different spring constants and different terminal force cues. As might be expected given the results of Tan and Durlach [14], the terminal force cue was sufficient to discriminate compliance, and thus we found no differences between the colocated and non-colocated conditions.

In the second study [17], we revisited non-colocated compliance discrimination in an object identification task with one notable change. We utilized virtual non-linear springs that featured the same terminal force. In this way, compliance discrimination was only possible if participants were able to integrate or combine the displacement of one hand with the force sensed in the other. We found that sensory integration in the non-colocated condition came at a cost in terms of object identification accuracy and identification duration. Tan and Durlach never considered an equal terminal force hypothesis in their experiments, but these findings suggest that the mechanical work cue and the compliance cue may be harder to perceive in the non-colocated condition than in the colocated condition.

Of course, each of these non-colocated displays also turns a unimanual task into a bimanual one, and bimanuality may carry a penalty with it. Bimanuality alone, however, does not immediately lead to degraded performance. In particular, bimanual interfaces that inherently present colocated action and reaction cues have been shown to result in better task accuracy and faster task realization, so long as attention is not too divided between the hands (see [18] for a review). In particular, Panday et al. [19] demonstrated that bimanual perception of curvature in large cylinders was better than unimanual perception. Likewise, Plaisier and Ernst [20] demonstrated that bimanual perception of stiffness was better than unimanual perception when both hands received both the displacement and force cues (redundant information). We acknowledge that in the non-colocated kinesthetic display we have proposed here, the hands no longer receive redundant information. Yet, the same was true of the bimanual non-colocated task of Dupin et al. [15].

While our most recent investigation of non-colocated compliance discrimination indicated that non-colocated force and displacement cues may not be integrated by the brain in a manner consistent with colocated force and displacement, the results were limited [17]. In particular, the findings are not generalizable beyond the three specific non-linear springs used. In addition, the presence of a bimodal distribution in the results suggests that learning effects were potentially confounding the results, along with a potential confound of an accuracy/time trade-off.

In this present study, we attempt to generalize the results of our prior experiment beyond the three springs to any compliant element without a salient terminal force cue. To accomplish this, we compare colocated and non-colocated compliance display in a compliance discrimination threshold task. Using an adaptive experimental protocol, participants adjusted the non-linearity of two compliant virtual springs until they were no longer distinguishable from one another. We also improved upon our training approach, as well as removed accuracy and time as task completion goals.

In addition to a comparison of colocated and non-colocated kinesthetic display, we also compare colocated

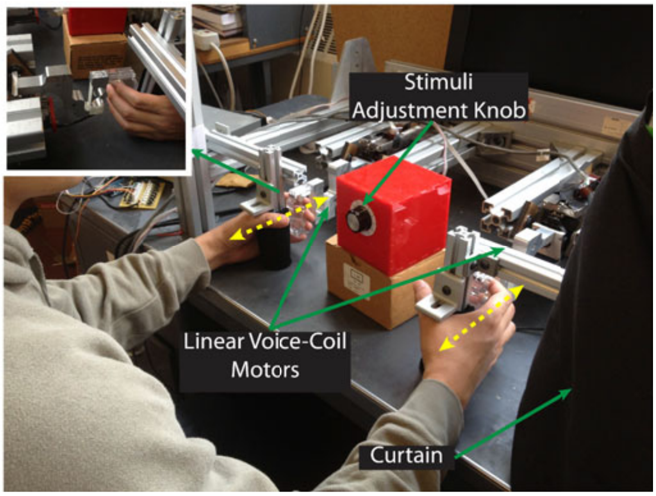

Fig. 1. Two single-axis linear voice-coil motors lying in the horizontal plane. Yellow dashed arrows indicate axis of motion. A stimuli adjustment knob contains a rotary knob with a position indicator. Inset figure shows grip attached to motor.

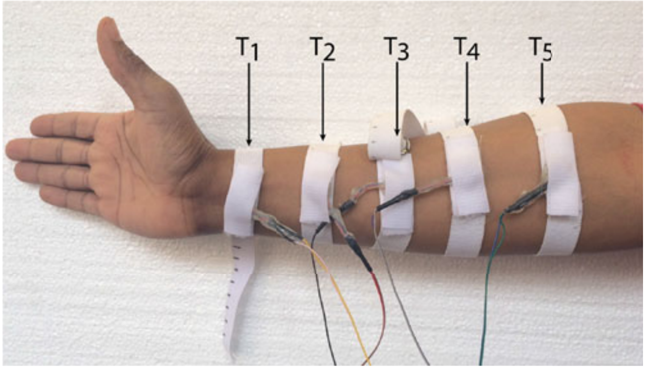

Fig. 2. Tactile array with five tactors attached to volar surface of the forearm with elastic straps.

and non-colocated kinesthetic display to vibrotactile display of force. While the results from this final comparison will be limited to the particular vibrotactile display used in this study, they will test a separate hypothesis: Non-colocated kinesthetic display is an appropriate model for vibrotactile display of force, without the confound of sensory substitution. We therefore expect compliance discrimination in the vibrotactile display to be less than the colocated display and less than or equal to the non-colocated kinesthetic display.

2 Methods

2.1 Participants

We tested N = 10 able-bodied participants (six males, four females; mean age = 24 $\pm$ 5 years). Only one participant in this experiment took part in one of the previous experiments, but the time gap between participation was 21 months. Nine of the 10 participants were right-hand dominant. Prior to starting the study, participants were given an overview of the experimental protocol approved by the University of Michigan Institutional Review Board, and informed consent was obtained.

2.2 Apparatus and Stimuli

2.2.1 Apparatus

The colocated and non-colocated kinesthetic display consisted of two, identical, linear, voice-coil motors each with a 30 mm throw lying parallel in the horizontal plane. Each motor was equipped with a linear optical encoder (US Digital EM1-0-500) and driven with a current sourcing amplifier (Advanced Motion Control 12A8). In addition, a 2 kg rated beam load cell (Transducer Techniques LSP-2) was mounted to monitor force between the user and each motor carriage. Grips were attached to the loadcells to allow the motors to be pulled when rendering the springs. Participants interacted with the motors by placing their palm on the palm-rest anchoring their thumbs and wrapping their fingers around the grip (see Fig. 1). A curtain was placed over the motors so participants could not see the motor movement.

A stimulus adjustment knob (see Fig. 1) was used to adjust the stimulus intensity level. The knob featured a position indicator along with a scale in order for participants to track their adjustments during the experiment. The scale featured graduation marks but was unnumbered so that participants had no numerical reference of intensity level between experimental conditions. In addition, a random gain was used to convert the rotation of the knob to a variation in stimulus intensity. This will be described in more detail in Section 2.4.

A small array of vibrotactile actuators (Pololu Shaftless Vibration Motor 10 $\times$ 3.4 mm) provided vibrotactile feedback on the volar surface of the forearm (see Fig. 2). The actuators were driven by an Arduino Mega I/O board and a custom transistor circuit. The tactors operated in the frequency range 0-133 Hz. The tactors were evenly distributed along the forearm between the bend in the wrist and the bend in the elbow with a 4 cm space between each tactor. Elastic straps were placed at each tactor location and adjusted so that their circumference was 3 cm less than the circumference of the forearm at each location to ensure a snug fit. The tactors were attached to the elastic strap with Velcro.

A Dell Precision T3500 Desktop computer with a Sensoray 626 PCI data acquisition card was used for data acquisition and computer control.

2.2.2 Stimuli

The stimuli consisted of a set of linear and non-linear virtual springs governed by the following constitutive law:

$$F = A\alpha x_d^2 + B\alpha x_d + Cx_d \tag{2.1}$$

where A = -0.0037 N/m^2, B = 0.111 N/m, and C = 0.667 N/m. The parameter x_d is the displacement of the spring measured in mm, and the parameter α controls the non-linearity of the spring. *(Note that this relationship describes a parabola in Cartesian space with variable vertex (36.06,* α*).)*

The set of virtual springs with different degrees of non-linearity was created by varying the parameter α on the interval $\alpha \in [-6, 6]$ in increments of 0.02, creating a total of 601 different springs. The following boundary conditions were placed on the springs:

$$F = \begin{cases} 20 \text{ N} & \text{if } x_d \geq 30 \text{ mm} \\ 0 \text{ N} & \text{if } x_d \leq 0 \text{ mm}. \end{cases} \tag{2.2}$$

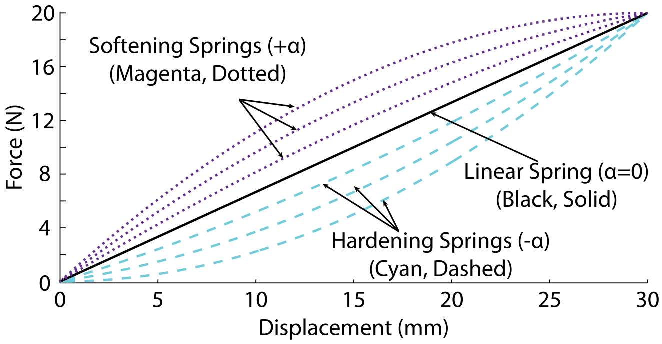

Fig. 3. Sample virtual springs. Springs each have a parabolic force/displacement relationship. Linear spring (Black, Solid) corresponds to $\alpha = 0$. Springs above the linear spring (Magenta, Dotted) correspond to $+\alpha$ and are 'softening' springs. Springs below linear line (Cyan, Dashed) correspond to $-\alpha$ and are 'hardening' springs.

For the case $\alpha = 0$, a linear spring is generated. All other springs given by $\pm\alpha$ are symmetric about this linear spring. A few select springs from the set are shown in Fig. 3. The springs above the linear spring correspond to $+\alpha$ and are 'softening' springs. The springs below the linear spring correspond to $-\alpha$ and are 'hardening' springs.

The virtual springs given in Equation (2.1) were rendered as extension springs in three different conditions. In the colocated condition, the motor held in the right hand (see Fig. 1; left hand/motor not used) was commanded to produce the force F as a function of x_d measured by the right motor carriage displacement. In the non-colocated condition, the motor held in the right hand (see Fig. 1) was commanded to produce the force F as a function of x_d measured by the carriage displacement of the motor held in the left hand. In the vibrotactile condition, the five tactors were temporally staggered in their actuation up the forearm as a function of x_d measured by the carriage displacement of the motor held in the right hand. Actuation started with the tactor closest to the wrist T_1 and ended with the tactor closest to the elbow T_5. The actuation of each tactor $T_i, i = 1, .., 5$ was governed according to the following expression:

$$T_i = Fm_t - (i-1)s_t,\ i = 1, \ldots, 5, \tag{2.3}$$

where F is the force from the spring given by Equation (2.1), $m_t = 0.75$ V/N, and $s_t = 2.5$ V. Note that the command to the tactors was limited to the voltage range (0, 5).

To determine the relationship between the command to the tactor T_i and the output frequency f, an analysis was conducted with a 3-axis accelerometer (Freescale MMA726). The accelerometer was attached to the surface of the tactor with adhesive, and both were attached to the forearm using the same elastic strap as in the experiment. Command voltages from 0-5 V were sent to the tactor. The resulting empirical relationship was fit by the following expression

$$f = \begin{cases} 0 \text{ Hz} & \text{if } T_i < 1 \text{ V} \\ k_h T_i + b_h \text{ Hz} & \text{if } 1 \text{ V} \le T_i \le 5 \text{ V}, \end{cases} \tag{2.4}$$

where $k_h = 20.75$ Hz/V and $b_h = 29.67$ Hz. Note that at least 1 V needed to be supplied to the tactors to initiate a consistent vibration of ~ 50 Hz.

2.3 Training

Participants were trained on the three different feedback conditions: colocated, non-colocated, and vibrotactile. In the training session participants were allowed to feel the linear spring ($\alpha = 0$), a hardening spring ($\alpha = -6$), and a softening spring ($\alpha = 6$) in each condition. The linear spring was presented first in each condition to help familiarize the participant with the given condition. The hardening and softening springs were then presented to the participant in each condition. All three springs were presented alongside a visual aid that showed their force/displacement profiles. Training was considered complete when the participant could correctly identify four random presentations of the springs in each condition without the visual aid.

2.4 Testing

Our testing protocol differs from the typical method of adjustments [21]. Rather than starting from a stimulus intensity level well above or below the threshold for each stage, our protocol borrowed from adaptive procedures in that the stimulus intensity for each stage was based on the final intensity of the previous stage. In addition, our protocol was designed to compare two variable stimuli, as opposed to one variable stimulus and one reference stimulus. The intent was to increase the efficiency of the test.

The spring's non-linearity was controlled through the stimulus adjustment knob. The mapping between the angular displacement θ of the knob and the parameter α was governed by the following equation:

$$\alpha = ({}^{-6}/_{\theta_n})\theta + 6, \tag{2.5}$$

where the parameter $\theta_n \in [100^\circ, 270^\circ]$ and was randomly selected by the computer at the beginning of each trial in increments of 10 degrees. This range was chosen based on pilot results to ensure participants were not memorizing the mapping between θ and α to accomplish the task. Clockwise turns of the knob increased θ and decreased α. Counterclockwise turns of the knob decreased θ and increased α, however θ was limited to non-negative values. If the knob was turned past θ_n, θ would reset to $\theta = 0$ and θ_n would reset to a new randomly selected value. This was done to penalize participants for randomly guessing where the springs were equal (corresponding to $\theta = \theta_n$, $\alpha = 0$).

In the test, participants were presented with a variable softening spring ($+\alpha$) and a variable hardening spring ($-\alpha$). As they adjusted the knob, they varied the non-linearity of both springs. The goal was to determine the smallest amount of non-linearity at which the springs could still be distinguished.

The test consisted of one trial for each of the three conditions, presented at random. In each trial, there were five stages. In Stages 1, 3, & 5 participants were instructed to adjust the knob clockwise until they just reached the point at which the springs were indistinguishable. In Stages 2 & 4, participants were instructed to adjust the knob counterclockwise until they could just notice the difference in the two springs. In each case, participants were allowed to adjust in the opposite direction if they felt they adjusted too far.

For Stage 1, the springs started at $\alpha = \pm 6$, the hardening and softening springs presented during training. For Stages

2-5, the starting value of α in each stage corresponded to the final value of α in the previous stage. At the start of each stage, participants were instructed to feel each spring before adjusting α. The spring presentation was controlled by the experimenter and presented to the participant as requested. After each adjustment of α, participants were allowed to feel the hardening and softening spring as many times as needed before making any further adjustments to α. The only requirement was that they felt the two springs an equal number of times per trial. Participants were allowed to take a break following each stage.

2.5 Metrics and Data Analysis

The kinematic and performance data were recorded to disk with a 1 kHz sampling rate. All data was down-sampled to 500 Hz, and subsequently filtered using a fifth order low-pass butterworth filter with a 5 Hz cutoff frequency.

Our metrics consisted of two threshold measures with respect to the non-linear parameter α, as well as the results from a post-test survey administered to each participant.

2.5.1 Performance Threshold Measures

The first measure, the Absolute Threshold (AT), is a measure of the smallest value of the non-linearity parameter α for which participants could detect two distinct stimuli. The second measure, the Separation Threshold (ST), is a measure of the value of the non-linearity parameter required for participants to notice a difference between the two stimuli. Note, this metric is very similar to the difference threshold found in traditional psychophysics studies. However, we are not comparing our variable stimulus to a fixed reference. In our case, the reference stimulus is also variable and is determined as the point at which the two stimuli feel equal.

As mentioned in the previous section, the test consisted of five stages for each of the three conditions. In stages 1, 3, & 5, participants were instructed to adjust α until they just reached the point at which the two stimuli were indistinguishable. These stages will be referred to as 'Equality Stages.' In stages 2 & 4, participants were instructed to adjust α until they could just notice the difference in the two stimuli. These stages will be referred to as 'Difference Stages.'

The Absolute Threshold for each condition was computed as the mean of the final α value in each of the last four stages. This corresponds to the final value of α at the end of Difference Stage 2 α_{D2}, Equality Stage 3 α_{E3}, Difference Stage 4 α_{D4}, and Equality Stage 5 α_{E5}, as shown in Equation (2.6) below. The final value of α for Equality Stage 1 α_{E1} was excluded from this measurement as it was considered an exploratory baseline for each participant:

$$\mathrm{AT} = \frac{\alpha_{D2} + \alpha_{E3} + \alpha_{D4} + \alpha_{E5}}{4}. \tag{2.6}$$

The Separation Threshold for each condition was computed as the mean difference between the final value of α for the last two Difference Stages and the last two Equality Stages. This corresponds to the difference between the final value of α in Difference Stage 2 α_{D2} and Equality Stage 3 α_{E3}, as well as between Difference Stage 4 α_{D4} and Equality Stage 5 α_{E5} as shown in Equation (2.7) below:

$$\mathrm{ST} = \frac{(\alpha_{D2} - \alpha_{E3}) + (\alpha_{D4} - \alpha_{E5})}{2}. \tag{2.7}$$

2.5.2 Post-Test Survey

Our post-test survey represents a qualitative self-assessment of each participant's perceived performance on the task, as well as a subjective assessment of the three conditions. The survey contained a mix of Likert-based, short-answer, multiple-choice, and ranking questions. The entire survey had 18 questions. Only the questions with quantitative responses will be discussed further.

Question 3 asked participants to choose on a scale of 1-7 (1-'very difficult' and 7-'very easy') how easy/difficult each condition was. Question 10 asked participants to choose on a scale of 1-5 (1-'strongly disagree' and 5-'strongly agree') how well they agree/disagree with the statement that the colocated condition required more concentration than the non-colocated or vibrotactile conditions. Question 11 was similar to question 10, except that it compared the non-colocated condition to the colocated and vibrotactile conditions. Question 12 was similar to question 11, except it compared the vibrotactile condition to the colocated and non-colocated conditions. Question 15 asked participants on a scale of 1-5 (1-'strongly disagree' and 5-'strongly agree') how well they agree/disagree with the statement "I would be able to perform the task while holding a conversation" in each of the three conditions. Question 16 asked participants to rank the three conditions in order of preference. In analyzing the results, the various levels of 'agree' and 'disagree' (i.e., 'strongly agree', 'somewhat agree', and 'agree') were grouped into a single 'agree' or 'disagree' category, due to the small number of participants. The same was done for the 'difficult' and 'easy' Likert-based questions.

2.6 Statistical Analysis

Linear mixed models (LMM) were used for the Absolute Threshold and Separation Threshold using SPSS (v.21) for estimating fixed and random coefficients. Within the model, participants were a random effect while condition was a fixed effect. For the Absolute Threshold, the final value of α in the last four stages is treated as a repeated measure. For the Separation Threshold, the two difference measures are treated as a repeated measure. Bonferroni adjustments were applied to the estimated means to control for Type I errors. A p-value of 0.05 was used as a threshold for significance.

3 Results

3.1 Compliance Discrimination Results

Overall, our participants were able to detect smaller differences in the non-linearity of the springs with colocated kinesthetic display than with non-colocated kinesthetic display, and smaller differences in the non-linearity of the springs with colocated kinesthetic display than with vibrotactile display. Participants took on average 10 ± 3 min and made 19 ± 8 finite adjustments of α in the colocated

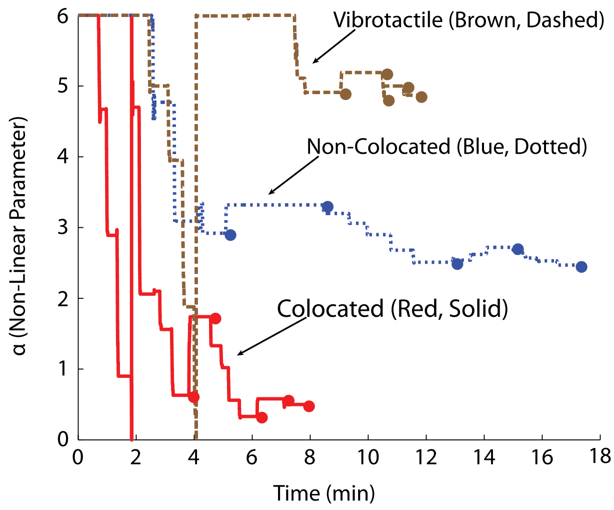

Fig. 4. Time-domain trajectory of α for a representative participant. Solid red traces represent the colocated condition. Dotted blue traces represent the non-colocated condition. Dashed brown traces represent the vibrotactile condition. Solid circles represent the end of each stage. This particular participant caused a reset of α in both the colocated and vibrotactile conditions by turning past $\alpha = 0$, $\theta = \theta_n$.

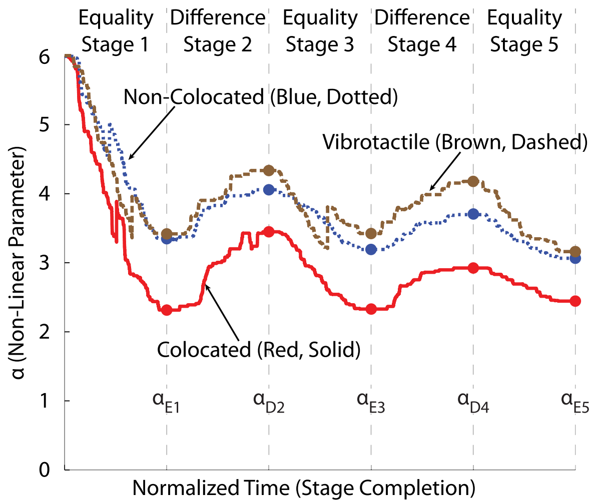

Fig. 5. Average trajectory of α for all participants in the three conditions. Time has been scaled and normalized to the completion of each stage prior to averaging. Solid red traces represent the colocated condition. Dotted blue traces represent the non-colocated condition. Dashed brown traces represent the vibrotactile condition. Solid circles represent the end of each stage. The large jumps in the trajectory are due to a reset in θ_n or large adjustments by certain participants.

condition, 12 ± 2 min and 16 ± 5 finite adjustments of α in the non-colocated condition, and 13 ± 5 min and 15 ± 6 finite adjustments of α in the vibrotactile condition. A representative sample participant's results are shown in Fig. 4, where 7.56 min and 15 adjustments were taken for the colocated condition, 16.45 min and 17 adjustments were taken for the non-colocated condition, and 9.90 min and 10 adjustments were taken for the vibrotactile condition. The final value of α in each of the five stages is indicated by the solid circles on the traces.

To show the collective results of all participants, the time-domain trajectory of α for each participant at each stage was time-warped to a standardized length. This was accomplished by normalizing the recorded trajectory of α for a given stage with respect to the duration of that stage. This was done separately for each condition and each stage for every participant. The resulting trajectories are combined and averaged for all 10 participants as shown in Fig. 5.

In the colocated condition, participants chose on average smaller values of α on all five stages of the experiment, including the three stages aimed at finding the point where the springs felt equal (*Equality Stages*), and the two stages aimed at finding the point where the springs felt noticeably different (*Difference Stages*).

The Absolute Threshold), taken as the mean of the final value of α in the last four stages (α_{D2}, α_{E3}, α_{D4}, and α_{E5}), was significantly smaller in the colocated condition (M = 2.8, SD = 1.4) than in the non-colocated condition (M = 3.5, SD = 1.3) ($\beta = -0.716$, SE = .271, p = 0.028) or the vibrotactile condition (M = 3.8, SD = 1.8) ($\beta = -0.988$, SE = .271, p = 0.001) (Fig. 6A). The Separation Threshold, taken as the mean of the difference in the final value of α between the last four stages ($\alpha_{D2} - \alpha_{E3}$ and $\alpha_{D4} - \alpha_{E5}$) was not significantly different for each condition (Fig. 6B).

The maximum force difference between the springs at the Absolute Threshold for each of the three conditions can be found in Table 1, along with the maximum force difference between the two non-linear springs in our prior experiment [17] for comparison. The maximum force difference occurred at x_d = 15 mm for each of the conditions due to the symmetry of the springs. Note the force differences are outside of 7 perecnt JND% reported for force sensing [22], [23].

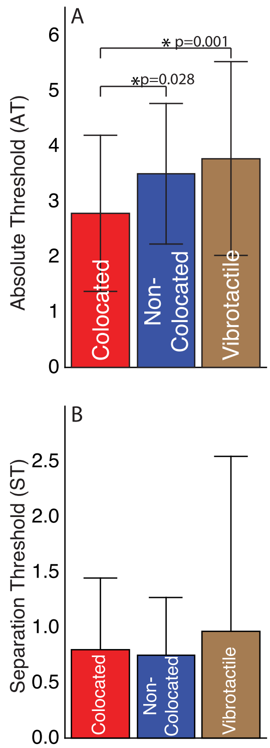

Fig. 6. Performance Threshold Measures. (A) Mean Absolute Threshold for all 10 participants in each of the three conditions. (B) Mean Separation Threshold for all 10 participants in each of the three conditions. Error bars represent 1 standard deviation.

TABLE 1
Maximum Force Difference between the Spring Pair at the Absolute Threshold for Each of the Three Conditions, Along with the Maximum Force Difference between the Two Non-Linear Springs in Our Prior Experiment [17]

	Max. Force Diff. (N)
Colocated	4.64
Non-Colocated	5.82
Vibrotactile	6.27
Prior Experiment	7.46

3.2 Survey Results

From a qualitative perspective, our participants preferred the colocated condition over the non-colocated condition and the vibrotactile condition (see Table 2). The majority of participants found the colocated condition less difficult than the non-colocated or vibrotactile conditions (Question 3). They found that the non-colocated and vibrotactile conditions required more concentration than the colocated condition (Questions 10-12). The majority of participants found that the task was difficult to complete in any condition while distracted (Question 15). Overall the majority of participants ranked the colocated condition first, the vibrotactile condition second, and the non-colocated condition third (Question 16).

TABLE 2
Post-Test Survey Results (# Responses)

		Difficult	Neutral	Easy
Question 3	CL	1	7	1
	NCL	6	2	1
	V	7	1	1
		Disagree	Neutral	Agree
Question 10	CL vs. NCL	8	1	1
	CL vs. V	7	1	2
Question 11	NCL vs. CL	3	0	7
	NCL vs. V	5	0	5
Question 12	V vs. CL	3	1	6
	V vs. NCL	4	0	6
Question 15	CL	6	4	0
	NCL	9	1	0
	V	8	1	1
		First	Second	Third
Question 16	CL	7	1	2
	NCL	1	3	6
	V	2	6	2

Colocated (CL), Non-colocated (NCL), and Vibrotactile (V). Question 3 only contains nine responses as one participant did provide a response to this question.

4 Discussion

In this study, we have determined that haptic displays that non-colocate kinesthetic action and reaction degrade compliance discrimination relative to displays that colocate kinesthetic action and reaction in the absence of a terminal force cue. We have arrived at this conclusion through a comparison of three haptic displays designed to connect a user to a pair of virtual non-linear springs that produce the same terminal force and posses variable non-linearity that can be adjusted by the user. What differs between these three displays is the manner in which the force/displacement relationship of each spring is made available to the user.

In our colocated kinesthetic display, the force/displacement relationship of the spring remains coupled through the interface, impinging at a single contact with the user's hand. In the non-colocated display, the force/displacement relationship of the spring becomes decoupled through the interface to impinge now on two hands; force in one hand and displacement in the other. By a similar token, in our vibrotactile display, the force/displacement relationship of the spring becomes decoupled through the interface and rendered to the user as a vibration/displacement relationship; one hand controls the exploratory displacement, and the arm receives the vibration.

Participants were able to detect smaller differences in the compliance of the non-linear springs when force and displacement cues were colocated with respect to the body as opposed to being non-colocated. While force discrimination and stiffness/compliance discrimination have been considered in the literature [14], [22], [23], [24], we are not aware of any work that has assessed the effect of action/reaction location on compliance discrimination.

While our previous study demonstrated that colocated displays may allow for better performance than non-colocated displays [17], the results were not generalizable in terms of the discrimination ability of each display. In this experiment, participants were able to discriminate springs in the colocated and non-colocated condition that were considerably more linear than the two non-linear springs in our prior study [17] (see Table 1). In addition, in our prior study it could be argued that the performance differences would diminish or disappear with training and more experience. Here, our results point to limitations that are potentially invariant with respect to training and increased exposure. Synthesizing the information from the left and right hands took more time in our prior study, however we placed no time limitations on participants to perform the task in this experiment.

In this experiment, we also considered compliance discrimination with force rendered through a vibrotactile display that modulated both vibration intensity (amplitude and frequency) and actuation pattern (spatial and temporal). Participants, however, were still able to detect smaller differences in the spring compliance with the colocated kinesthetic display than the vibrotactile display. Compared to the non-colocated kinesthetic display, there were no significant differences in compliance discrimination. While this result may only hold for our particular vibrotactile display, it suggests that non-colocated kinesthetic display may be a good model for vibrotactile display of force, without the confound of sensory substitution. Like our non-colocated kinesthetic display, the vibrotactile display is non-colocated in that the exploratory displacement and resulting force rendered as a vibration are dissociated or impinging on different locations on the participant's body. Thus, even if the salience of a vibrotactile cue were normalized to the salience of a kinesthetic cue (perhaps in terms of equalized JNDs), it can be expected to nevertheless degrade perception relative to a colocated kinesthetic display.

Although we found significant differences in the absolute threshold in this experiment, there were no significant differences in the separation threshold. This suggests that participants were not turning the knob at random—θ_n was different for each condition and for each participant. Apparently there existed a certain difference in non-linearity that participants needed to experience in order to feel comfortable that the two springs were in fact different. This difference did not seem to be affected by the type of display. This finding also correlates well with the fact that we found no differences in the number of probes (and probe rate) of our prior experiment [17].

Overall, the qualitative results of our experiment suggest that the colocated condition was easier than both the non-colocated and the vibrotactile condition. While our participants thought the entire task was difficult, they felt that the colocated condition was easier than the vibrotactile condition, and the vibrotactile condition was easier than the non-colocated condition. That the non-colocated condition ranked the lowest of our three conditions highlights how unnatural this condition is. This last place ranking, however, was not borne out in our quantitative results where compliance discrimination was not significantly different between the non-colocated condition and the vibrotactile condition. Overall, the majority of participants thought both the non-colocated and vibrotactile condition were most difficult, suggesting that the difficulty arose from the fact that both displays required the brain to integrate sensory information from separate parts of the body.

The integration of haptic signals from different hands does not always suggest degraded perception. For example, recent literature suggests that bimanual haptic interfaces can lead to improved task accuracy and faster task realization [18], resulting in better curvature perception for larger cylinders [19] and better stiffness perception [20]. Still, other studies have demonstrated that bimanual hatic perception may not be superior to unimanual perception, due in part to the fact that the brain tends to trust sensory information more from the dominant hand [25], the hand with superior proprioception [26], or the sensory cues from both hands independently [27]. None of these studies, however, involved bimanual haptic perception with non-colocated sensory cues, which was the prominent feature of the conditions investigated in this study.

Recently, Dupin et al. demonstrated that even when the cues are displayed in a non-colocated manner to the hands (dissociated), the brain simplifies the task of bimanual integration by treating the dissociated signals as if they came from the same hand [15]. Note that the cues being investigated by Dupin involved kinesthetic action and cutaneous reaction without sensory substitution. Here, we have demonstrated that when the dissociated action and reaction cues are both kinesthetic, the brain is not not able to integrate them as well. This also appears to be true when the kinesthetic reaction cue is substituted with a cutaneous cue such as vibration.

The degradation in compliance discrimination performance in the non-colocated condition relative to the colocated condition is therefore quite intriguing, especially considering that in both conditions the same force would be produced at the same displacement for a given spring. Likewise, in both conditions the force was displayed to the participant's right hand. In the colocated condition, the right hand was also controlling the displacement, however, there is little evidence to suggest force sensitivity is affected by movement of the limb; the JND% for force has been reported as 7 percent for both the isometrically contracted arm [22] and the active pinching hand [23]. The only difference then between conditions is the hand that controlled the spring's displacement. While it has been shown that the limb associated with the non-dominant hand is more accurate at static proprioception [28], [29], the results on dynamic proprioception are not as conclusive [26], [30]. Yet, even if there were a non-dominant hand bias, it would likely result in better proprioception in the non-colocated condition for all but one of our participants who was left-hand dominant. Still, despite these facts, the brain appears to struggle with integration of the dissociated force and displacement kinesthetic cues.

It may be possible to explain differences in compliance discrimination between the colocated and non-colocated displays if we consider the manner in which each display mechanically couples the body to the spring. In the colocated display, the hand and spring are mechanically coupled at their point of contact. Therefore, in addition to sensing the spring's displacement and force, the hand is able to perform mechanical work on the spring, and the spring can perform mechanical work on the hand. The mechanical work cue was first determined to be important for compliance discrimination of objects with rigid surfaces by Tan and Durlach [14]. Thus, in the colocated condition, participants are privy to force, displacement, and mechanical work cues.

Considering now the non-colocated display where one hand controls only the displacement of the spring and the other hand feels only the resulting force, the spring and hands are mechanically coupled in a fashion that does not occur naturally. In this new coupling, neither hand is capable of performing mechanical work on the spring, nor is the spring capable of performing mechanical work on either hand. Therefore, in the non-colocated condition, participants are only privy to force and displacement information without a mechanical work cue. In their work, Tan et al. found that compliance discrimination was poor when the terminal force and mechanical work cue are no longer salient. This finding correlates well with our observations of compliance discrimination in the non-colocated condition. Of course, we are not able to test this mechanical work hypothesis in isolation given that the non-colocated display introduces the additional feature of bimanual operation. There may be a penalty associated with bimanual operation relative to unimanual operation in that the brain must integrate sensory signals from two hands rather than one. We have not independently quantified that penalty in this paper, thus we are not able to attribute the performance degradation associated with non-colocation strictly to the removal of the mechanical work cue. However, since energy and mechanical work are certainly organizing principles in physical system dynamics, it might provide a good candidate as a perceptual cue. We believe that the present findings motivate future work that would independently quantify the contributions of the mechanical work cue and unimanual/bimanual operation to perceptual acuity in colocated and non-colocated haptic displays.

In terms of mechanical coupling, the vibrotactile display is quite different from both the colocated and non-colocated displays. Because force was converted to vibration, the vibrotactile display is not capable of mechanically coupling hand and spring, and mechanical work was not performed by the hand nor the spring. Therefore, in the vibrotactile condition, participants are only privy to force and displacement information as in the non-colocated condition. Like the non-colocated display, the mechanical work hypothesis cannot be tested in isolation because the vibrotactile condition introduces the confound of sensory substitution.

While the findings presented in this study answer a fundamental question regarding the potential impact of haptic displays that dissociate kinesthetic action and reaction cues, they also suggest in the application sense that not all haptic displays are created equal. In particular, sensory substitution of kinesthetic cues through cutaneous display, while advantageous for many reasons including economy and ease of implementation, can have the unintended consequence of presenting to the user a non-colocated display that can limit perception. One application where this is particularly relevant is that of upper-limb prosthetics, where vibrotactile display is often used to display grip force [5], [6], [7], [8], [9], [10], [11], [12]. Based on our findings, it is now possible to see that a vibrotactile display for prosthetic grip force may limit the amputee's ability to perceive an object's compliance through their prosthesis. This is especially true considering that many of the objects we encounter in the real world have non-linear stiffness characteristics. Note that a non-linear stiffness relationship can suggest brittleness or a tendency to break. It would seem appropriate then to consider the development of colocated kinesthetic displays for myoelectric prostheses. This is the manner in which a body-powered prosthesis works, and partly contributes to its prominence today, despite remaining relatively unchanged in design since its development over 60 years ago [31]. Certain research has already been undertaken toward this aim [16], [17], [32].

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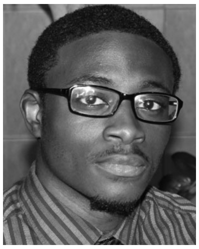

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