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Perception of Mechanical Properties via Wrist Haptics: Effects of Feedback Congruence

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***Abstract*— Despite non-co-location, haptic stimulation at the wrist can potentially provide feedback regarding interactions at the fingertips without encumbering the user's hand. Here we investigate how two types of skin deformation at the wrist (normal and shear) relate to the perception of the mechanical properties of virtual objects. We hypothesized that a congruent mapping (i.e. when the most relevant interaction forces during a virtual interaction spatially match the haptic feedback at the wrist) would result in better perception than other mappings.We performed an experiment where haptic devices at the wrist rendered either normal or shear feedback during manipulation of virtual objects with varying stiffness, mass, or friction properties. Perception of mechanical properties was more accurate with congruent skin stimulation than noncongruent. In addition, discrimination performance and subjective reports were positively influenced by congruence. This study demonstrates that users can perceive mechanical properties via haptic feedback provided at the wrist with a consistent mapping between haptic feedback and interaction forces at the fingertips, regardless of congruence.**

I. Introduction

Mechanical properties of real-world objects, such as mass, stiffness, friction, and temperature are often perceived via direct touch at the fingertip (Fig. 1). One goal of haptic display is to recreate interaction sensations to make the user perceive these mechanical properties. Many multi-degree-of-freedom fingertip devices have been developed to render interaction forces during active exploration and manipulation tasks in virtual environments [1]–[3]. These devices can achieve high levels of perceived realism, good dexterity, and useful communication of information (e.g., the mechanical properties of objects) during manipulation tasks.

There is a desire to reduce the mechanical size and design complexity of high-performance haptic devices and decrease the cost of actuators. However, it is difficult to achieve all these outcomes. In addition, users cannot wear fingertip devices in certain applications, e.g., augmented reality, where it is desirable to leave the fingertips free to interact with physical objects. To account for these limitations, we propose a different approach to provide artificial haptic feedback by relocating haptic sensations from the fingertip to the forearm, near the wrist. In doing so, the calculated forces from interactions between the fingertips and manipulated virtual objects are rendered on the skin of the arm.

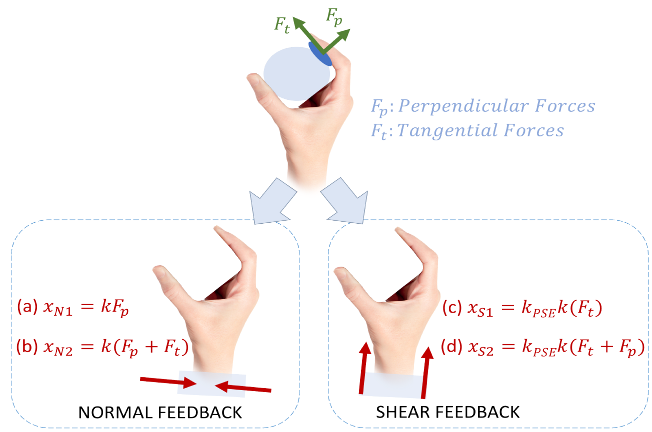

Fig. 1. Haptic conditions used to study perception of mechanical properties. Interaction forces perpendicular F_p and tangential F_t to the virtual fingertip are mapped into relocated haptic cues as (a) only the perpendicular component in the normal feedback direction, (b) both perpendicular and tangential components in the normal direction, (c) only the tangential component in the shear feedback direction, or (d) both perpendicular and tangential components in the shear direction. k is a mapping constant that converts the interaction forces to actuator displacements in the normal direction and k_{PSE} represents the ratio between normal and shear feedback to create equal intensities for each participant individually, such that conditions $N2$ and $S2$, rendering the same force components, feel the same.

In this scenario, users cannot receive realistic feedback because they interact with virtual objects through their fingers but perceive the haptic feedback on their arms. Such haptic feedback creates believable interactions by conveying useful information about fingertip contact and material properties of objects without increasing cognitive load for the user, such that it qualitatively adds to (rather than detracts from) the user experience. Such relocation has been previously used successfully for social interactions [4]–[8], communication [9]–[11], navigation [12], and teleoperation [13], [14]. In addition, previous wrist devices [15]–[17] provided feedback to the wrist in a distributed manner and showed that relocated haptic feedback could create better user perception during virtual interaction tasks compared to no haptic feedback.

It is unknown how the direction of applied force to a user's skin at or near the wrist should be exploited to enhance the perception of the mechanical properties of virtual objects (Fig. 1). We previously designed haptic bracelets to render either normal (perpendicular to the skin) or shear (parallel to the skin) feedback near the wrist, and measured users' performance in discriminating virtual objects based on stiffness with normal vs. shear feedback [18]. Our results showed that participants were more accurate with normal feedback, and shear feedback did not feel as strong as normal. In the same article [18], we conducted a second study and found

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that normal and shear stimuli cannot be equalized through skin deformation in displacement or interaction forces across all users. Instead, they should be equalized on the point of subjective equality using the staircase method in a calibration process. With this information, we now aim to determine how the force directions calculated at the fingertips should be mapped to force directions at the wrist. In this study, we focus on examining the effects of feedback congruence at the wrist on perception of virtual mechanical properties.

II. Hypotheses and Experiment Design

Interaction forces occur between an avatar and a manipulated object with perpendicular and tangential components to the fingertip. These force components are mostly affected by mechanical properties of the objects and how users interact with them. While discriminating stiffness, participants examine the object by squeezing and perceive perpendicular forces to their fingertips [19], [20]. While discriminating mass, participants examine the object by lifting it between two fingers and perceive tangential forces to their fingertips. Similarly, while discriminating friction, participants examine the object by sliding a finger tangentially to its surface and perceive tangential forces to their fingertips. We designed a study to investigate the impact of force direction at the wrist and congruent vs. noncongruent mappings between fingertip forces during virtual interactions and the deformation at the wrist using haptic conditions in Fig. 1.

Congruence can be defined as the correlation between the magnitude of properties [21] or the existence of an expected quantitative relationship between properties, e.g., if an object feels the way one would assume it would be based on its appearance [22]. In this paper, we define congruence operationally as the most relevant and intuitive relation between haptic feedback and expected interaction forces during a task to assess a mechanical property [19]. Congruence changes depending on the property being assessed. While discriminating stiffness, users expect to perceive interaction forces perpendicular to their fingertips, so we achieve congruence when perpendicular forces are rendered on the user's wrist in the normal direction ($N1$). While discriminating mass and friction, users expect to perceive interaction forces tangential to their fingertips, so we achieve congruence when tangential forces are rendered on the user's wrist in the shear direction ($S1$). Any other mapping is considered noncongruent.

We hypothesized that participants' perception of mechanical properties would be better in terms of discrimination accuracy with a congruent mapping between force at the fingertips and deformation at the wrist than different versions of noncongruent mapping. The advantages of such congruence are clear for rendering at the fingertips [1], [23], and we propose that this should extend to relocated haptic feedback. In addition, we hypothesized that participants' perception of mechanical properties would be worsen in terms of discrimination accuracy when the relevant component of interaction forces are withdrawn from the rendered haptic feedback. Our experiment uses two different sets of tasks performed in a virtual environment to investigate these hypotheses.

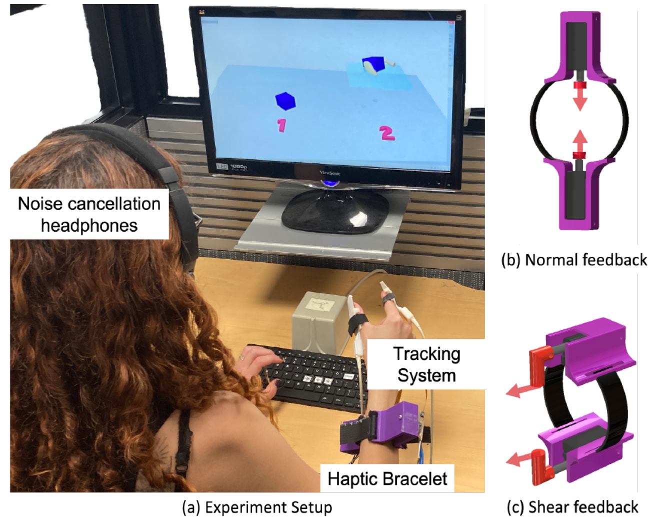


Fig. 2. Experiment setup adapted from our previous work [18]: (a) The participant sits in front of a monitor and wears a fingertip tracking sensor and noise cancellation headphones. She interacts with objects in the virtual environment while interaction forces are rendered on the wrist through haptic bracelets with (b) normal feedback or (c) shear feedback.

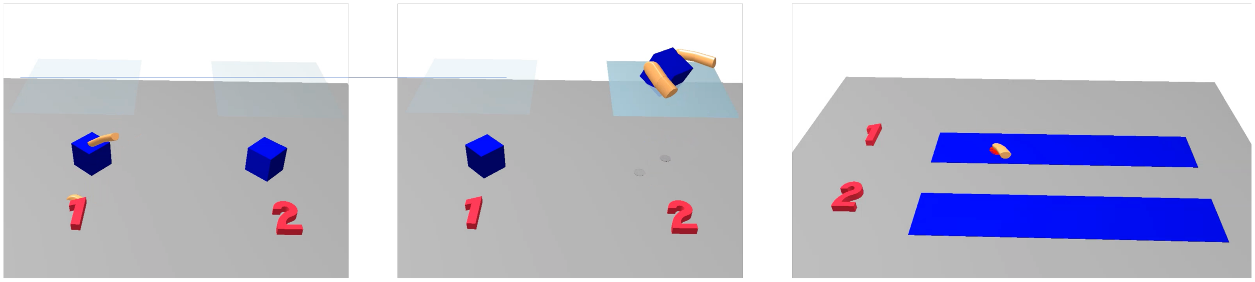
- In one set (main discrimination tasks), we measure how well participants can discriminate mechanical properties (stiffness, mass, and friction) of a pair of virtual objects. We inform participants which mechanical property varies, and instruct them on how to explore the virtual objects. We measure participants' performance in terms of just noticeable difference and point of subjective equality for each mechanical property.
- In another set (open-response tasks), we explore how participants interpret the rendered object mechanical properties (stiffness, mass, or friction) of a pair of virtual objects. Unlike the previous set, we present participants the virtual objects *without* telling them which mechanical property varies or how to interact with these objects. These open-response tasks take place before and after performing the main discrimination tasks.

III. Experiment Setup

Fig. 2 shows the experiment setup. The participant sits in front of a monitor and interactswith objects in a 3D virtual environment where a table, two objects/surfaces, and two fingers are visible. An electromagnetic tracking system tracks movements of the participants' right (dominant) index finger and the thumb to control the virtual fingers in real time. When there is an interaction between the virtual fingers and virtual objects, interaction forces are computed and rendered near the wrist using the haptic bracelets. To minimize the effect of environment and actuator auditory noise, the participant wears headphones that play white noise and cancel external noise.

A. Wrist Haptic Devices (Haptic Bracelets)

We use two haptic bracelets, applying normal or shear forces on the user's skin, as shown in Fig. 2. Each bracelet has two actuator sets on the dorsal and ventral sides of the forearm while their orientation determines the force



(a) Stiffness Discrimination (b) Mass Discrimination (c) Friction Discrimination

Fig. 3. Experiment tasks in the virtual reality environment for (a) stiffness discrimination, (b) mass discrimination, and (c) friction discrimination.

direction. We chose Actuonix PQ12-P linear actuators due to low weight (15 g), maximum stroke (20 mm), high output force (18 N), and straightforward control using an integrated position sensor. Users wear the bracelet on their forearm near the wrist to minimize the impact of wrist movements and facilitate consistent physical contact. The 3D-printed base grounds the actuator to the user's body and is designed with a curvature to fit the forearm, a silicone pad between the plastic and the skin, and wide Velcro straps to keep the grounding stable. Further details about the design and performance are described in [18].

B. Virtual Environment

We created a virtual environment in Fig. 2 using the CHAI3D framework [24]. The user's finger movements are tracked at approximately 200 Hz using a trakSTAR tracking system and an Ascension Model 800 sensor attached to the user's finger through 3D-printed grounding. The virtual environment, which is shown on a 2D monitor and updated at 144 Hz, displays the virtual finger pose, as well as the virtual objects with which the user interacts (Fig. 3).

As the virtual scene updates, the CHAI3D framework calculates interaction forces between the virtual object and the haptic proxy point associated with each finger and represented with virtual finger components. These forces are based on the distance between the proxy point associated with each finger and the virtual object limits, the environmental factors (gravity, etc.), and the physical properties of the virtual object with which the user is interacting. These forces are computed in perpendicular or tangential components with respect to the virtual fingertip.

IV. Experiment Procedures

A. Participants

14 participants (age 23-33, 7 females and 7 males, all right-handed) joined the study. The Stanford University Institutional Review Board approved the experimental protocol, and all participants gave informed consent. Before the experiment, participants reported their haptic experience on a scale between L0 (no experience) and L7 (expert). 1 participant reported L2, 3 participants reported L3, 2 participants reported L5, 1 participant reported L6, and 7 participants reported L7.

B. Calibration

To compare the perceptual and performance differences of congruent feedback rendered on the wrist, we must ensure that the participants perceive both stimuli equally [18]. Upon arrival, the experimenter helps the participant wear both bracelets on user's arm (first on the right side, then on the left). Bracelets are located 35 mm away from the wrist bone, and tightened with similar pressure using the marks assigned on the Velcro straps. The tightness is further adjusted until the participant confirms that both bracelets feel equally intense with no actuation to initiate the calibration phase.

During the calibration, normal stimulus is actuated with 1 and 3 mm displacements as a reference while shear stimulus is actuated with a varying displacement set by the staircase method. The participant is asked to compare both stimuli and verbally adjust the shear (i.e. increase or decrease). Based on these comments, the staircase method computes the next displacement value for the shear until both stimuli feel equally intense, as previously detailed [18]. For each reference value, a shear displacement is found that created a sensation of equal intensity. Using these displacements, we modeled a linear, personalized relationship between normal and shear stimuli for each participant.

On day 1, we recorded the measurement marks assigned on the Velcro straps for each participant. These recordings were used to tighten the Velcro straps with the same intensity as day 1 - so no additional calibration was needed.

C. Main Discrimination Trials

During the main discrimination trials, the participants see two identical virtual objects with different simulated mechanical properties (Fig. 3) to interact using their dominant hand.At every trial, they perform a two-alternative forced-choice task: interact with two virtual objects and report which object had the larger value of the mechanical property relevant to that task (stiffness, mass, or friction).Unlike the calibration, participants wear only one bracelet at a time, rendering normal or shear feedback on their right (dominant) wrist.The procedure for each mechanical property was as follows:

Stiffness: In each trial, participants are given two identical-looking virtual cubes with different stiffness values and identical mass and friction values (Fig. 3(a)). They squeezed each object to evaluate the stiffness, either by *(i)* pushing down with one finger from the top, *(ii)* squeezing with two fingers from the sides when the object is on the ground, or *(iii)* squeezing with two fingers from the sides when the object is lifted. They could choose one of these strategies, change their strategy when desired, or use alternative strategies during a trial. They were also allowed to interact with each object as many times as needed to confidently report which object felt stiffer.

Mass: In each trial, participants are given two identical-looking virtual cubes with different mass values and identical stiffness and friction values (Fig. 3(b)). They grabbed each object using two fingers (thumb and index finger) and lifted them until reaching a target plane located near the ceiling of the work space. As the object passed through the target, its opacity changed from semi-transparent to completely opaque, indicating that they have lifted the object sufficiently to have explored its mass. They were allowed to give an answer only if both targets had become opaque. They were also allowed to interact with each object as many times as needed to confidently report which object felt heavier.

Friction: In each trial, participants are given two identical-looking virtual strips with different friction values and identical stiffness and mass values (Fig. 3(c)). They pushed their index finger onto the strip until the shadow of the index finger turned red, and slide their finger along the strip. Thanks to this visual cue, they were guided to push on the strip a sufficient amount to generate friction force. They were allowed to interact with each strip as many times as needed to confidently report which strip has higher friction.

To choose the stiffer/heavier/higher-friction object/strip, participants typed on the keyboard the number that appeared next to the corresponding virtual object. Then, they pressed on the space key to start the next trial.

The participants perform a manipulation task in four haptic feedback conditions as detailed in Fig.1: normal feedback with perpendicular forces ($N1$), normal feedback with perpendicular and tangential forces ($N2$), shear feedback with tangential forces ($S1$), and shear feedback with perpendicular and tangential forces ($S2$). Whether these haptic conditions are congruent or not depends on the nature of the discrimination task: normal feedback with perpendicular forces ($N1$) is congruent for stiffness discrimination tasks, and shear feedback with tangential forces ($S1$) is congruent during mass and friction discrimination tasks, respectively.

D. Open Response Trials

In each trial, participants were presented with two identical-looking virtual cubes, similar to the mass trials shown in Fig 3(b). The cubes differed in only one mechanical property and were the same in the other two properties. Unlike the main discrimination trials, participants were not told which property differed between the two cubes, but they were asked to comment verbally on any difference they felt. They were allowed to interact with each object as many times as desired until they provided a response. Similar to the main discrimination trials, participants wear only one bracelet at a time, rendering normal or shear feedback on their right (dominant) wrist.

E. Experiment Flow

Combining the two types of trials described above, we designed the experiment as in Fig. 5. The trials were conducted over two days with a maximum of 2 hours per day. The experiment was divided into two days, such that the participants experienced only one direction of haptic feedback each day. Half of the participants received normal haptic feedback on the first day and in the shear haptic feedback on the second day, while the other half received shear haptic feedback on the first day and normal haptic feedback on the second day.The order for the normal/shear feedback and the stiffness/mass/friction discrimination blocks within the main experiment were pseudo-randomized across participants. For each block, the participant first perceives the haptic condition with both perpendicular and tangential force components, and then only the perpendicular or only the tangential components – such that the lack of one component would not impact how the participants learn to perform the task. There were 2-minute breaks after every 50 trials and 5-minute breaks between each mechanical property block.

F. Metrics and Analysis

Participants' responses were recorded during the experiment and analyzed based on subjective comments and discrimination performance. Subjective comments are reported to help us evaluate the overall experience and participants' preferences. Discrimination performance is analyzed by averaging the correct answers while identifying the object with the higher value. The average values obtained from different comparison pairs can create a psychometric curve using:

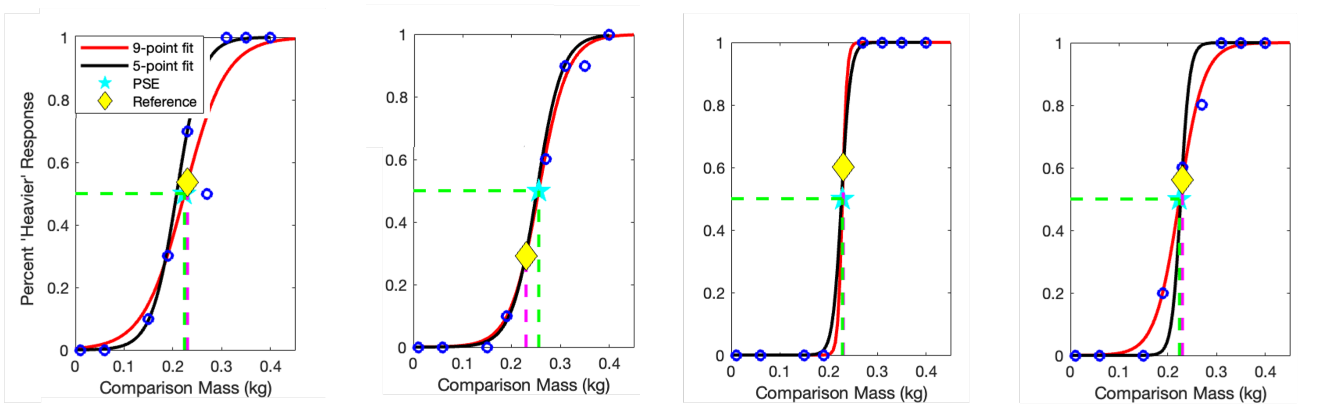
$$y = \frac{1}{1 + e^{\frac{\alpha - x}{\beta}}}, \tag{1}$$

where y is the proportion of participants' responses with higher property, x is the comparison value, α is the point of subjective equality (PSE), and β is a slope fitting parameter. The values of α and β are determined from the fit of the sigmoid function. Just noticeable difference (JND) is then calculated by subtracting the PSE (α) from the comparison weight corresponding to $y = 0.75$. Fig. 4 shows sample psychometric curves fit a single participant's responses collected during mass discrimination for all haptic conditions.

G. Pilot Study and Reference/Comparison Values

We performed a pilot study with one participant to identify appropriate of reference and comparison values for each mechanical property. We have set nine comparison values for three mechanical properties (stiffness, mass, friction), and four haptic conditions (normal feedback with perpendicular forces, normal feedback with all forces, shear feedback with tangential forces, shear feedback with all forces as detailed in Fig. 1). The pilot study participant repeated each of these conditions ten times, resulting 1080 trials in total.

The orders of the comparison values were pseudo-randomized within the blocks of fixed varying property to minimize effects of presentation order. Through this process,



(a) Normal Feedback, Perpendicular Forces ($N1$)
(b) Normal Feedback, All Forces ($N2$)
(c) Shear Feedback, Tangential Forces ($S1$)
(d) Shear Feedback, All Forces ($S2$)

Fig. 4. Sample psychometric curves during mass discrimination for each of the four haptic conditions with 9 data points (red), and 5 data points selected among the recorded 9 points (black). The psychometric curves were fit to the participant's responses and used to calculate the PSE and JND for each haptic condition.

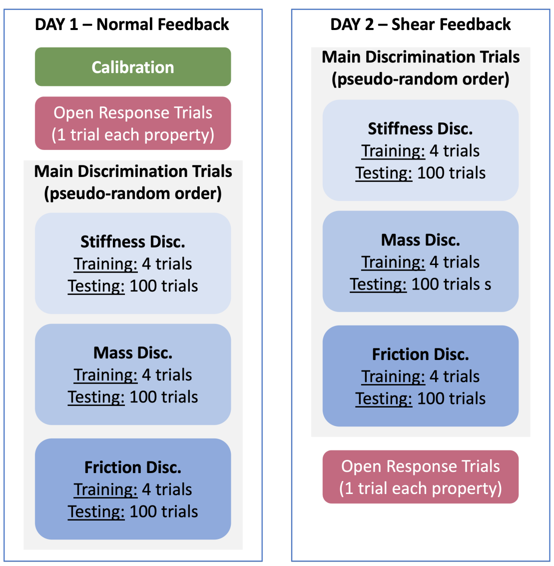


Fig. 5. Experiment flow and the number of trials in terms of the feedback direction, experiment sections, and mechanical properties to examine. The order of the comparison values, property blocks, and feedback direction assigned to each day were pseudo-randomized for each participant.

we found a set of comparison values that resulted valid psychometric curves for all haptic conditions.

As a result of the pilot study, we defined the reference and comparison values for each mechanical property to be used during the main discrimination trials(Section IV-C). Five comparison values were then deemed sufficient to reproduce the psychometric curve with a reasonable-length experiment to avoid user fatigue. For stiffness discrimination tasks, we used a reference stiffness of 340 N/m and comparison stiffness values of 80, 210, 340, 470, or 600 N/m while the mass values of 0.23 kg and friction values of 2 Ns/m are kept constant. For mass discrimination tasks, we used a reference mass of 0.23 kg and comparison mass values of 0.06, 0.15, 0.23, 0.31, or 0.4 kg while the stiffness values of 130 N/m and friction values of 2 Ns/m are kept constant. For stiffness discrimination tasks, we used a reference friction of 1.5 Ns/m and comparison friction values of 0.1, 0.75, 1.5, 2.25, or 3 Ns/m with the stiffness values of 80 N/m and mass values of 0.23 kg are kept constant. Stiffness values were selected to be low enough not to interfere with the friction sensation and high enough to avoid creating the perception of delay between the visual and haptic cues during interaction.

For the open-response trials (Section IV-D), participants interacted with two objects with the minimum and the maximum comparison values from the main discrimination trials (80 to 600 N/m for stiffness, 0.23 to 0.4 kg for mass, and 0.1 to 3 Ns/m for friction). The other property values that are set constant as the reference values detailed above.

Our hypotheses were that participants would perform the best with congruent feedback, and they would perform the worst when a seemingly relevant force component was missing from the feedback. During the pilot study, we found that discriminating mechanical properties without the relevant force component was still possible using other visual and haptic cues and specific exploration strategies. For example, during the stiffness discrimination task, users can squeeze the object *after* lifting the object at a certain height. Even when the seemingly relevant normal forces are not provided, the tangential forces communicate stiffness due to the relationship between normal force and friction resisting gravity. During the mass discrimination task, when the object is lifted, the user has to squeeze a heavier object more to prevent the object from slipping. Similarly, during the friction discrimination task, users have to apply more or less force normal to the surface in order for the finger to slip or not slip visually. Due to the pilot's use of specialized strategies to achieve tasks without the use of seemingly relevant force cues, we kept all feedback conditions in the study.

V. Results

All 14 participants completed the experiment, which was then analyzed in terms of the performance during the main discrimination tasks, open response question answers, and subjective comments.

A. Main Discrimination Trials

Fig. 6 shows box-and-whisker plots for PSE and JND for all participants and haptic conditions for stiffness, mass, and

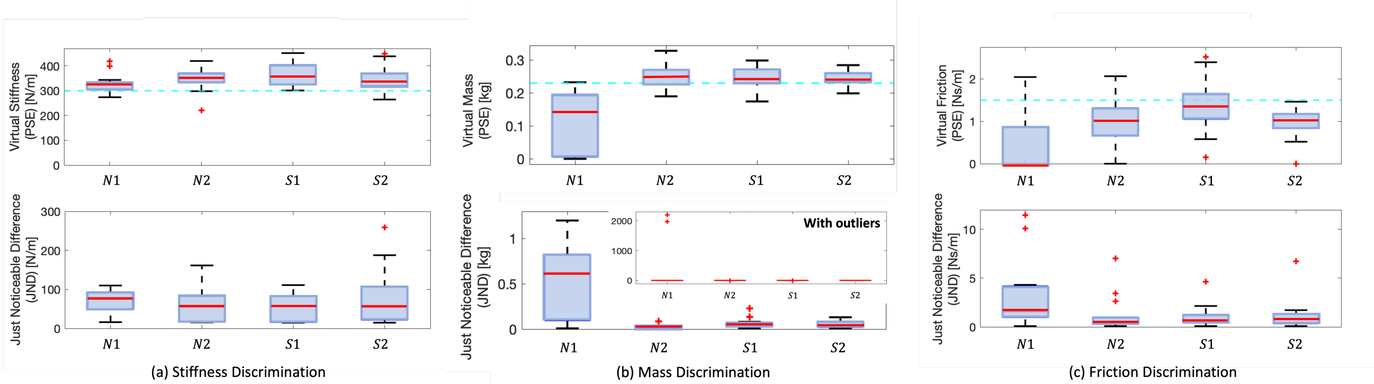


Fig. 6. Box-and-whisker plots of PSEs and JNDs for each haptic condition across all participants during (a) stiffness discrimination, (b) mass discrimination, and (c) friction discrimination task. Haptic condition $N1$ is normal feedback with perpendicular forces, $N2$ is normal feedback with all forces, $S1$ is shear feedback with tangential forces, and $S2$ is shear feedback with all forces. Median values for JND and PSE are reported in Tables I and II.

TABLE I
MEAN AND MEDIAN PSE FOR ALL HAPTIC CONDITIONS ACROSS 14 PARTICIPANTS

Property	Value	*N1*	*N2*	*S1*	*S2*
Stiffness [N/m]	Mean	332.6771	344.3033	365.4016	345.1270
	Median	330.3108	349.7266	355.8845	337.0397
Mass [kg]	Mean	0.1432	0.2528	0.2281	0.2442
	Median	0.1420	0.2490	0.2435	0.2404
Friction [Ns/m]	Mean	0.4375	1.0664	1.4716	1.0506
	Median	0.0000	1.0512	1.3922	1.0276

TABLE II
MEAN AND MEDIAN JND FOR ALL HAPTIC CONDITIONS ACROSS 14 PARTICIPANTS

Property	Value	*N1*	*N2*	*S1*	*S2*
Stiffness [N/m]	Mean	66.1280	60.3466	57.4971	78.6644
	Median	79.0740	55.0245	57.3669	54.9602
Mass [kg]	Mean	298.1383	0.0273	0.0617	0.0496
	Median	0.0640	0.0305	0.0457	0.0391
Friction [Ns/m]	Mean	3.2515	1.1288	0.8369	0.7919
	Median	1.8039	0.4702	0.6054	0.7368

friction discrimination tasks. Tables I and II summarize the mean and the median values of the computed results.

1) Stiffness Discrimination: We performed a one-way repeated-measures analysis of variance (ANOVA) on PSE and JND with haptic condition as the main factor. There was no statistically significant effect of haptic condition on PSE ($F(3,55) = 1.120, p = 0.349, \eta^2_{partial} = 0.061$) or JND ($F(3,55) = 0.537, p = 0.659, \eta^2_{partial} = 0.030$). We also performed independent t-tests to determine if there was a significant difference between PSE and the reference stiffness value for each haptic condition. The results showed that PSE was significantly different from the reference *only* with noncongruent feedback ($S1$, $p = 0.01367$).

2) Mass Discrimination: We performed a one-way repeated-measure ANOVA on PSE and JND with haptic condition as the main factor. There was no statistically significant effect of haptic condition on JND ($F(3,55) = 2.165, p = 0.108, \eta^2_{partial} = 0.143$) but we found a statistical significance on PSE ($F(3,55) = 22.092, p < 0.001, \eta^2_{partial} = 0.630$). A post-hoc Tukey test showed that the haptic condition of normal direction with perpendicular forces ($N1$) was statistically significantly different than all other conditions ($p < 0.001$), while there was no difference between the rest of the conditions.

We also performed independent t-tests to determine if there was a significant difference between PSE and reference mass value for each haptic condition. The results showed that PSEs were significantly different than reference when perpendicular forces were rendered in the normal direction, ($N1$, $p = 0.0334$) and all interaction forces were rendered in the normal direction ($N2$, $p = 0.0487$) and in the shear direction ($S2$, $p = 0.0377$); but not with feedback congruence ($S1$, $p = 0.0749$).

3) Friction Discrimination: We performed a one-way repeated-measures ANOVA on PSE and JND with haptic condition as the main factor. There was no statistically significant effect of haptic condition on JND ($F(3,55) = 3.163, p = 0.068, \eta^2_{partial} = 0.463$) but we found a statistical significance on PSE ($F(3,55) = 5.092, p = 0.019, \eta^2_{partial} = 0.581$). A post-hoc Tukey test showed that the haptic condition of normal direction with perpendicular forces ($N1$) was statistically significantly different than all other conditions ($p < 0.001$), while there was no difference among the rest.

We also performed independent t-tests to determine if there was any significant difference between PSE and the reference friction value for each haptic condition. The results showed that PSEs were significantly different than the reference when only the perpendicular forces were rendered in the normal direction ($N1$, $p < 0.001$) and all interaction forces were rendered in the normal direction ($N2$, $p = 0.0032$) and in the shear direction ($S2$, $p < 0.001$), but not with feedback congruence ($S1$, $p = 0.8568$).

4) Discussion: Our results showed that feedback congruence did not affect JND values, suggesting no difference in how well participants report changes in each of the three mechanical properties tested.Thus, the perceptual resolution of normal and shear haptic cues are independent from their applied mechanical property, as expected.

However, we found a significant negative impact of absent relevant force component on PSE for mass and friction discrimination tasks, and a positive significant impact of feedback congruence on PSE when compared to the reference values. Particularly, perceived friction and mass values were not found to be significantly different from the reference *only* with feedback congruence. On the other hand, perceived stiffness values were found to be significantly different from the reference *only* with feedback noncongruence. In sum, participants can still adopt a strategy to compare the mechanical properties of virtual objects with noncongruent feedback (resulting in reasonable JND values) but our results indicated a bias in perception under these strategies (resulting in a shift in PSE). Further work is needed to understand the reasons and the limitations for this bias.

Participants performed the stiffness discrimination tasks better than the rest, regardless of feedback condition. This could be due to the simplicity of the task - which has also been observed in the subjective comments. The experimenter reported that participants preferred exploring the stiffness property by squeezing the object without lifting it, resulting mostly perpendicular interaction forces to the fingertips. Thus, the interaction forces were not influenced by mass or friction. However, mass and friction discrimination tasks are a lot more complex, and the participants perceive interaction forces affected by all three properties simultaneously - even only when the tangential force components are rendered on user's wrist. We believe that the difference between the results of stiffness discrimination tasks and mass/frictiın discrimination tasks might be due to these difference between exploration procedures and interaction forces.

B. Open Response Results

Before and after the main discrimination trials, participants were given two identical-looking cubes, where one mechanical property, unbeknownst to the participants, differed. They were asked to verbally state what felt different between these cubes in their own words. Fig. 7 shows the number of participants who identified each varying property based on the experimenter's interpretation of the participants' responses before (pre-study) and after (post-study) the main trials.

		PRE-STUDY			POST-STUDY			
		RESPONSES			RESPONSES			
		STIFF.	MASS	FRICT.		STIFF.	MASS	FRICT.
VARYING PROPERTY	STIFF.	12/14	7/14	2/14	STIFF.	14/14	6/14	1/14
	MASS	4/14	13/14	5/14	MASS	1/14	14/14	5/14
	FRICT.	1/14	9/14	9/14	FRICT.	0/14	2/14	10/14

Fig. 7. Results of open-response trials to identify differences in mechanical properties between two objects, as perceived by haptic feedback applied to participants' wrists.

Previously, a similar experiment was performed with six participants using fingertip (rather than wrist) haptic devices [2]. Participants identified: friction better with the fingertip devices than with the bracelet, stiffness better with the bracelet and mass similarly. The results of these two studies suggest that perception of mechanical properties with the bracelet is possible, and their performance could be similar to fingertip devices.

C. Subjective Comments

After the experiment, participants completed a survey in terms of experiment difficulty, task difficulty and favorite feedback direction. We find no consensus on experiment difficulty or favorite feedback direction, even though they emphasized the negative impact of the lack of relevant component of the interactions.

1) Experiment Difficulty: Participants evaluated the difficulty of the overall experiment on a scale from L1 (easy) to L7 (difficult). One participant reported L1, 3 participants reported L2, 3 participants reported L3, 4 participants reported L4, 2 participants reported L5, and 1 participant reported L6. We observed an inverse relationship between the participants' haptic experience scale (see Section IV-A) and the experiment difficulty scale. The participant who reported L2 on the haptic experience scale reported L6 on the difficulty scale. In contrast, the participants who reported L7 on the haptic experience scale chose either L1, L2, or L3 on the difficulty scale.

2) Task Difficulty: Participants reported the difficulty of each discrimination task on a scale of 1 (easiest) to 3 (hardest). Fig. 8 shows the numbers of participants reporting the corresponding answer. Most (10) participants reported that the stiffness was the easiest among the three tasks, as expected due to simplicity of the task (as previously discussed in Section V-A.4 Then, the majority of the participants reported that the friction was the hardest among the three tasks, as expected since the rendered forces directly depend on the velocity of the user's finger movement, causing the task to be more dynamic than the rest.

Easy	1	2	3	Difficult
Stiffness	10	4	0	
Mass	3	10	1	
Friction	1	0	13	

Fig. 8. Reported task difficulty for stiffness, mass, and friction discrimination tasks on a 3 points scale by the 14 participants.

3) Feedback Direction: Participants reported which feedback direction they enjoyed the most. 8 participants reported shear, 5 participants reported normal, and 1 participant reported the same. In addition, we asked them to report which feedback direction was easier to notice during the discrimination experiment. 5 participants reported shear, 4 reported normal, and 5 reported the same. Several participants also commented that haptic feedback did not feel responsive when the congruent force component was absent. However, they did not seem to realize any difference between the feedback directions when all interaction forces were rendered.

VI. Conclusion

In this work, we studied the impact of feedback congruence, which has been defined as the mapping between the direction of key forces for virtual interactions and the rendered feedback on the user's skin, with the assumption that the computed interaction forces and rendered feedback should have the same direction. We compared the effects of haptic feedback rendered on users' wrists in the normal and shear directions with alternative force mapping modalities while discriminating stiffness, mass, and friction values of virtual objects. Our results showed that participants' perception of mechanical properties was not affected by the feedback direction. However, their perception was better in terms of discrimination accuracy when they received congruent feedback (i.e., when the relevant interaction force component from the fingertip was mapped to the wrist) compared to noncongruent feedback (i.e. irrelevant single force components or multiple force components). The subjective comments we collected showed no consensus on preferred feedback directions acting on the skin. While there might be various reasons why designers should choose one feedback direction or another, user performance in identifying mechanical properties of virtual objects is not significantly affected by feedback direction. In other words, after designing the haptic device with a particular feedback direction, different rendering strategies might be explored to improve the user performance of discrimination accuracy and user experience.

Congruence can alternatively be defined and investigated as the mismatch between the direction of interaction forces and the direction of rendered forces to the skin - *force-based congruence*. In the future, we can investigate the impact of using normal and shear haptic feedback while rendering only the perpendicular interaction forces during stiffness discrimination tasks, or only the tangential interaction forces during the mass and friction discrimination tasks.

Our study highlights perceptual trends related to feedback congruence, and a larger number of participants is needed to make stronger quantitative claims. In the future, we will investigate the effects of congruent and noncongruent force mappings under more realistic use cases. We will also study the perceptual differences between relocating the haptic feedback to the wrist and rendering the haptic feedback on the fingertips. In addition, we will extend the work to haptic stimulation at other locations on the body, such as the upper arm and waist, which might be advantageous for various applications, including navigation and social touch.

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