Effects of Haptic Feedback on the Wrist during Virtual Manipulation

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***Abstract*— As an alternative to thimble devices for the fingertips, we investigate haptic systems that apply stimulus to the user's forearm. Our aim is to provide effective interaction with virtual objects, despite the lack of co-location of virtual and real-world contacts, while taking advantage of relatively large skin area and ease of mounting on the forearm. We developed prototype wearable haptic devices that provide skin deformation in the normal and shear directions, and performed a user study to determine the effects of haptic feedback in different directions and at different locations near the wrist during virtual manipulation. Participants performed significantly better while discriminating stiffness values of virtual objects with normal forces compared to shear forces. We found no differences in performance or participant preferences with regard to stimulus on the dorsal, ventral, or both sides of the forearm.**

I. INTRODUCTION

In the real world, mechanical properties of objects, such as mass, stiffness, and temperature, are mostly perceived via touch (Fig. 1(a)). Haptic devices aim to recreate the same feeling for virtual interactions. Many multi-degree-of-freedom fingertip devices have been developed to render the interaction forces during active exploration/manipulation tasks in a virtual environment, as shown in Fig. 1(b) [1], [2]. A combination of their degrees of freedom of these devices and the high density of mechanoreceptors in the fingerpad are thought to improve the performance and perceived realism of manipulation tasks.

However, fingertip devices must be miniaturized to reduce encumbrance. Such a requirement complicates the design and increases the cost of actuators, which must have relatively large output force, small size and light weight. Furthermore, users cannot be asked to wear fingertip devices during certain applications, e.g. in situations where it is desirable to leave the fingertips free to interact with physical objects, as during augmented reality. We examine a different approach to artificial haptic feedback by relocating the delivery of haptic sensation from the fingertip to the forearm. In doing so, the mechanical properties of manipulated virtual objects are rendered on the arm (Fig. 1(c)).

Asking users to interact with virtual environments through their fingers but giving haptic feedback to their arm cannot provide perfectly realistic feedback. Instead, we posit that haptic signals, which merely hint at the real properties of an object, might be sufficient to create interpretable or "believable" interactions. Previous perception studies showed

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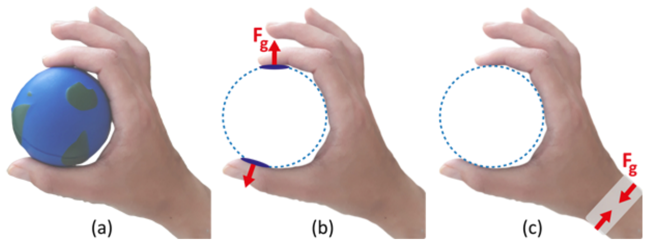


Fig. 1. Grasping tasks with different types of haptic feedback: (a) In the real world, the fingers directly contact the object. (b) In a virtual environment with fingertip haptic devices, grasp forces are displayed on the fingertips. (c) In a virtual environment with a wearable haptic device, grasp forces are displayed on the forearm near the wrist.

that visual cues have a significant impact on the overall perception when accompanied by haptic feedback [3]–[5]. This trend shows the potential of turning the typical requirement of realism into a new requirement of believability for a virtual manipulation task. In this context, believable haptic feedback conveys information about fingertip contact and material properties of objects, and is informative about the performance of actions without increasing cognitive or attentional load in the user, such that it qualitatively adds to (rather than detracts from) the user experience.

A. Background

The literature includes many studies where haptic feedback is given to a user's wrist, upper arm, or lower arm. Vibrotactile cues are commonly used to deliver event-related cues, such as notifications or warnings [6]–[8]. Such vibration feedback can also be used to enhance realism for scenarios where vibration is directly relevant, as in the case of music experiences [9]. However, vibrotactile cues can convey a very limited information. Thus, some researchers have examined skin deformation, squeezing, and other haptic modalities in wearable bracelets, with the type of feedback used highly dependent on the application.

Wearable bracelets (or arm bands) have been used to emulate the sensation of human touch in social interactions [10]–[14]. Others map haptic cues to directions for navigation [15], [16] or communication [17]–[19]. Wearable bracelets have also been used to render interaction forces during teleoperation tasks [20] or hand prosthesis control [21]–[23]. They can also be used to improve the learning process for surgical trainees in robotic surgical systems [24].

Other studies have examined details of the effects of type and location of haptic feedback. Biggs *et al.* [25] investigated the relative effectiveness of tangential over normal displacements of skin for producing tactile sensations at the fingertip and forearm. During an experiment, the user is given a normal reference displacement and asked to adjust the control displacement using a knob until the intensity of the control signal is felt similar to the reference. As a result, users chose tangential displacements almost half of the normal displacements, indicating a significantly higher sensitivity to tangential displacement. These results are based on the intensity of signals, while the perception might be different.

Tasbi is a multisensory haptic wristband delivering squeeze and vibrotactile feedback [26]. It features a novel mechanism for generating evenly distributed and purely normal squeeze forces around the wrist. A perceptual study was designed in which users experienced different object stiffness, control-to-display (C/D) ratio or both of them as Tasbi renders interaction forces. The results show that Tasbi can make a difference in terms perception for both C/D ratio and stiffness changes. Bellowband [27] is a pneumatic wristband for haptic feedback with vibration and localized pressure through eight pneumatic bellows based on layers of polyester thermoplastic polyurethane (TPU). Similarly, WRAP [28] provides highly effective directional cues using a set of four wearable restricted aperture pneumatic (WRAP) pouches worn near the wrist. Tasbi, Bellowband, and WRAP squeeze the wrist in a distributed manner using different actuation methods to offer effective haptic solutions.

Moriyama *et al.* [29] developed a five-bar linkage mechanisms with 2-DoF to present haptic feedback to the forearm during virtual interactions. A perceptual experiment was performed where haptic feedback based on the normal or shear directions is applied at the ventral side or the dorsal side of the wrist. Then, users were asked to evaluate and compare different feedback modalities based on the "strangeness" feeling they create on users. Their results show that skin stretch have similar feelings at different locations, while normal forces feel less strange when applied at the ventral side of the wrist. Despite of the inspirational ideas regarding wearable wrist devices and perception, we found it difficult to map the strangeness metric toward practical design guidelines.

The impact of different locations and the number of contact points applying forces to a user's skin on the perception, task performance, and learning curve of virtual manipulation tasks is still unknown. Previously, we performed a set of experiments based on haptic sketches by simulating interaction forces on user's arm manually [30]. We applied normal forces, sliding forces and skin stretch to user's wrist at the dorsal side as users interact with the virtual environment. Even though we eliminated the option for sliding forces, users reported that both normal forces and skin stretch felt natural and intuitive with their interactions. This preliminary study motivated us to develop mechatronic prototypes and conduct the studies presented in this paper.

B. Research Questions

The goal of this work is to understand the perception of wearable haptic bracelets during virtual manipulation tasks performed with a single finger. We developed a two-alternative forced-choice experiment in which users were asked to interact with two virtual objects with different stiffness values and choose the stiffer object. In particular, users move their index fingers to push and press virtual objects, which require both perception and manipulation. In return, they receive haptic feedback in the direction of normal and shear forces, on the dorsal, ventral or both sides around their wrist. The study aims to answer the following questions:

- In which direction should the interaction forces be applied to the arm?
- Where the forces should be applied?
- What is the effect of the number of contact points?

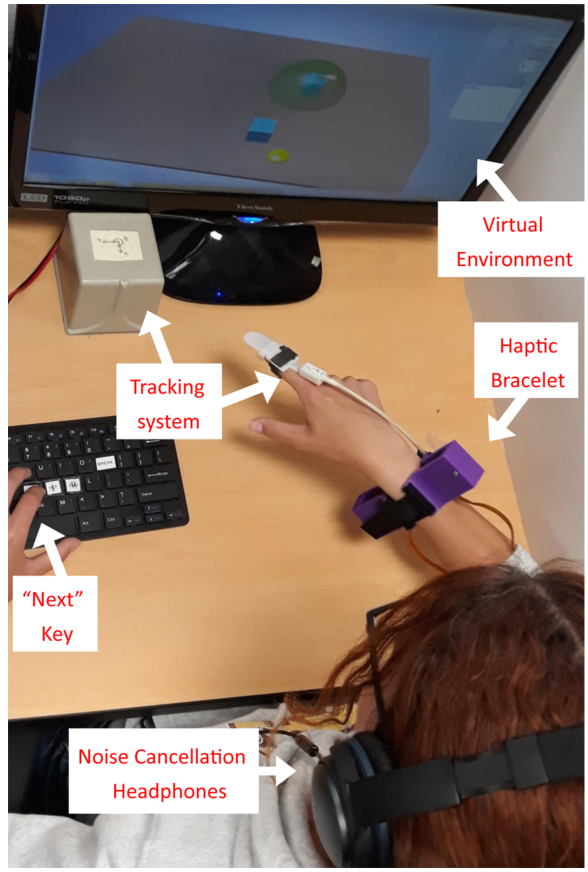


Fig. 2. Experiment setup: A user sits in front of a monitor and wears a haptic bracelet, a fingertip sensor for the tracking system, and noise cancellation headphones. Users are asked to interact with objects in the virtual environment, as the haptic device renders the interaction forces.

II. Experimental Setup

With the motivation of answering the aforementioned questions to improve the perception and performance of virtual tasks, we designed an experimental setup with haptic systems, a virtual environment and tracking system as shown in Fig. 2.

A. Haptic Feedback

One goal of this work is to investigate the effect of force direction (normal versus shear) on perception during virtual interaction. Linear actuators are a promising approach because they can be implemented for both directions with identical control performance and force output. In particular, Actuonix PQ12-P has the best combination of size (15 g), maximum stroke (20 mm), high output forces (18 N), and easy controllability via an integrated sensor for our study.

For the prototype devices, we selected grounding/orienting of linear actuators to enable investigation of both direction and location of forces acting around the wrist. The direction of forces is adjusted by designing different grounding parts as depicted in Fig. 3. In particular, grounding the linear actuator vertically on the wrist applies normal forces as the displacement is controlled (Fig. 3(a)). Alternatively, grounding the actuator horizontally creates skin stretch with a double side tape preventing the end-effector to slip through the skin (Fig. 3(b)). The reference displacement and force for each version are identical, because the same actuator is used for both directions.

The impact of location (dorsal or ventral) and number of contact points (one or two) are investigated by placing individual actuators on dorsal and ventral sides of the arm for both normal and skin stretch devices, as shown in Fig. 4. To minimize the impact of grounding diversities, we asked users to wear both components at all times, while we choose to actuate the component on the (i) dorsal side, (ii) ventral side, or (iii) both sides of the arm.

B. Virtual Environment

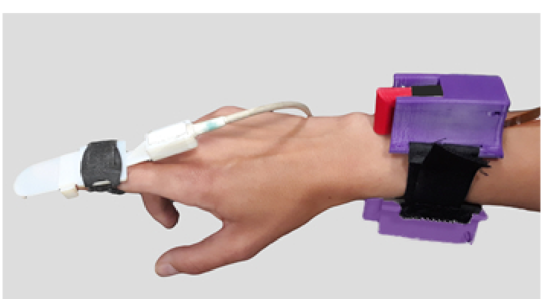
We created a virtual environment using the CHAI3D framework [31]. During the experiments, the virtual environment is displayed on a regular monitor and updated at 144 kHz. User's finger movements are tracked at approximately 200 Hz using a trakSTAR tracking system and an Ascension Model 800 sensor attached on user's finger through 3D printed grounding.

C. Experiment Task

In the experiment, users see two identical box objects which have different simulated stiffness values (see Figs. 5 and 6). Users are asked to move their index finger so that their avatar in the virtual environment interacts with these virtual objects. Specifically, they are asked to press on each objects, to evaluate their stiffness, and to drag the stiffer object to the target zone. The experiment has two modes: training and testing. During the training mode, the target zone changes color based on user's answer, such that if the user's answer is right, the zone turns green, and if the answer is wrong, the zone turns red as shown in Fig. 5. During the testing mode, the target zone does not change color, but changes transparency based on the validity of user's answer, regardless the answer (Fig. 6).

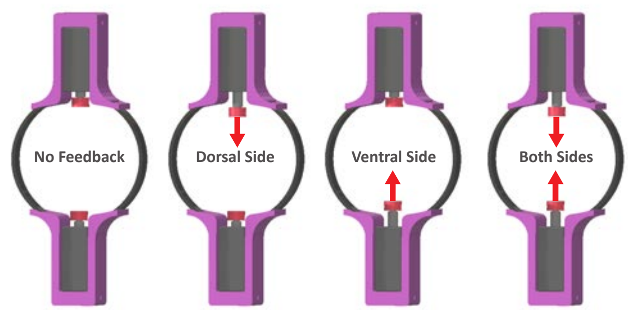
As the user interacts with the virtual boxes, desired forces to be rendered are computed based on the stiffness values of the boxes. Although in principle the actuators should render the desired *force*, the chosen linear actuators are position controlled. Thus, desired forces are expressed in the form of desired displacements using a fixed force-to-displacement ratio 0.03 N/mm [32]. Even though hairy skin was previously reported as 0.03 N/mm for normal and 0.04 N/mm for shear directions, whether skin stiffness is different around the wrist

(a) Device with normal force

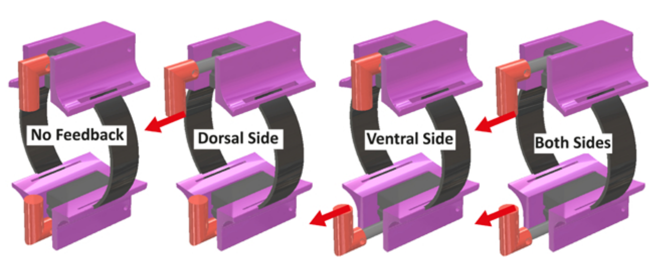


(b) Device with skin stretch

Fig. 3. User wearing the fingertip tracking sensor and a prototype applying (a) normal, and (b) stretch/shear forces to user's skin.



(a) Normal force



(b) Skin stretch

Fig. 4. As users interact with virtual objects, they receive haptic cues based on desired displacements in the direction of (a) normal and (b) stretch/shear forces on the dorsal, ventral or both sides of the wrist. Slip is prevented using a double-sided tape.

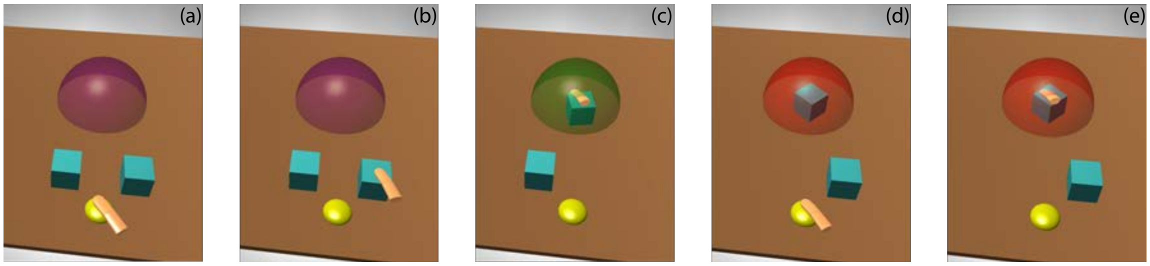


Fig. 5. Experiment task during training: (a) A new trial starts with a target zone, base zone, and two visually identical objects with different stiffness values. (b) The user presses on each object and chooses the stiffer object based on the haptic feedback. (c) If the answer is right, the zone turns green. (d) If the answer is wrong, the zone turns red. (e) The user goes back to the base zone and starts the next trial by pressing the "Next" key on the keyboard.

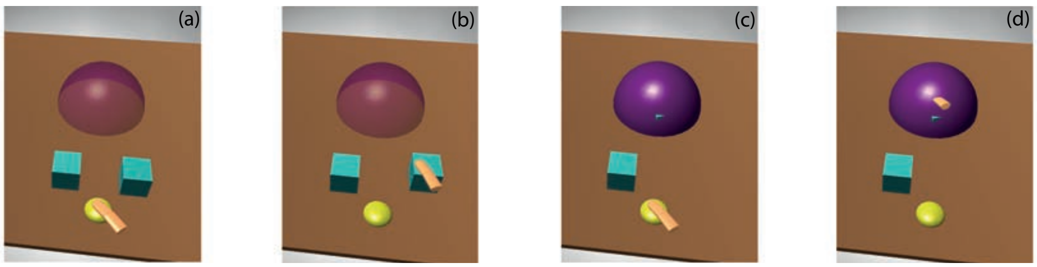


Fig. 6. Experiment task during testing: (a) A new trial starts with a target zone, base zone, and two visually identical objects with different stiffness values. (b) The user presses on each object and chooses the stiffer object based on the haptic feedback. (c) If the answer is valid, the transparency of the zone changes, regardless the answer. (d) The user goes back to the base zone and starts the next trial by pressing the "Next" key on the keyboard.

for the dorsal and ventral sides is still unknown. Furthermore, Biggs and Srinivasan showed that hairy skin is three times more sensitive to shear displacements than normal [25]. Considering all of these statements, instead of trying to ensure that interaction forces despite of the uncertainties, we propose to keep the level of displacements the same for different conditions.

As a compromise of both studies, we decided to keep the level of displacements the same for both normal and shear directions. Once the desired displacements are computed, an analog output sends the desired displacement to the Actuonix linear actuator controller (LAC).

During the entire experiment, users wear noise cancellation headphones playing white noise, to avoid environmental noise as well as the noise coming from the actuators.

D. Experimental Protocol

The experiment has two conditions: the direction of forces (normal forces / skin stretch) and the location of forces (dorsal side / ventral side / both sides). These 2 conditions can be ordered in 12 different ways, so we recruited 12 volunteers to participate in the study. Each participant performs the task with a different order of conditions.

The overall experiment is composed of two parts, one for each direction of force. For each part, there is a training block with 24 trials and 3 testing blocks with 16 trials each. Each testing block renders forces from one location of forces, while the training block covers all of the locations with a predefined order. Once the part is completed, the user is asked to wear the bracelet with the other force direction and repeat the entire procedure. Between each block and part, the user was given a break time to rest as needed.

During the experiment, the stiffness value of one object is kept at 300 N/mm. The stiffness of the other object is pseudo-randomized among 100, 200, 400, and 500 N/mm. The locations of the two objects is randomized.

We also ask users to fill a questionnaire, to comment on the haptic experience. All users are asked to choose (Q1) the direction of forces they liked the most, (Q2) the direction of forces that was easiest to notice, (Q3) the location of forces they liked the most, and (Q4) the location of forces that was easiest to notice.

III. Results and Discussion

A. Stiffness Discrimination Accuracy After Training

Most users reported that they felt comfortable identifying the stiffness of virtual objects through the haptic feedback acting on their forearm. However, a few users reported that they could not relate receiving the haptic cues around their wrist as they interact with virtual objects with their fingertips. According to them, the haptic cues could give sufficient information to discriminate different stiffness values in the virtual environment, but they felt the lack of realism. They also reported that they felt more comfortable in the end of the experiment compared to the beginning.

Due to these comments, we began our analysis by calculating the accuracy of users' responses during training; the results are shown in Fig. 7. Based on self-reporting, we categorized the users as having "no haptics experience" or "haptics experience" to highlight their previous experience with other haptic devices. We found that performance was not correlated with haptics experience ($R = 0.90$, $p = 0.01$). Fig. 7 (a) shows that 5 users out of the 12 achieved greater

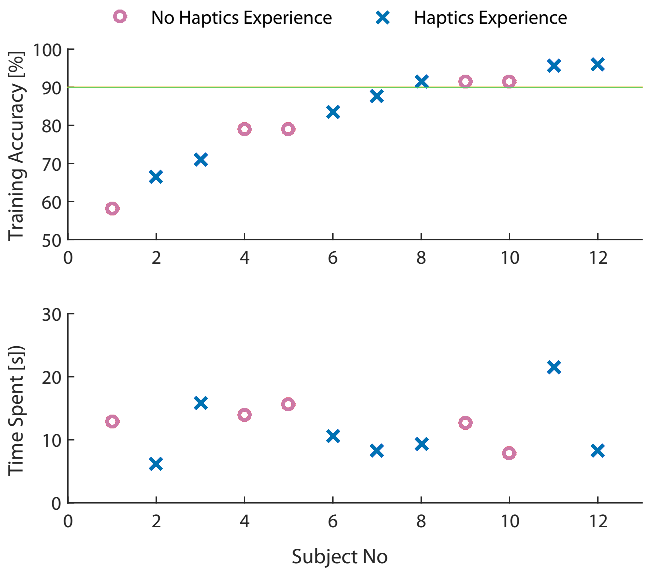


Fig. 7. Average accuracy and time spent to complete a trial during training for all users, ordered by accuracy. (a) Almost half of the users showed better performance than 90%. Users' performance during training was not related to their haptic experience. Chance performance is 50% (b) The average time spent for each subject has no correlation neither for the previous haptic experience nor the training accuracy.

than 90% accuracy after training, indicating high performance in interpreting the haptic cues. All users' accuracy were greater than chance, which is 50%.

Fig. 7 (b) shows the average time each subject spent to complete a trial during training. This plot shows that even though subjects with no haptic experience tend to spend more time to complete the task during training, we found no correlation among subjects with and without haptic experience, or less and more than 90% training accuracy.

B. Effect of Direction of Haptic Feedback

Our first research question asked in which direction (normal or skin stretch) the stimulus should be applied. Fig. 8 shows the accuracy of users' responses across all locations and stiffness comparisons. We split the results based on our classification of users' accuracy during training: >90% accuracy, <90% accuracy, and total (all users). One-tailed t-tests were performed to test for significant differences between the normal and skin stretch directions. Over all users, normal forces resulted in significantly better stiffness identification compared to skin stretch (t(11) = 2.96, p = 0.0129). When we analyzed further among users based on their training performance, we found that normal forces are significantly better for users with less than 90% accuracy during training (t(6) = 3.16, p = 0.0196), but not for those with better than those with greater than 90% accuracy during training (t(4) = 1.09, p = 0.338). Fig. 8 also shows the average time users spent to complete each trial with haptic feedback in the two directions. There was no significant difference between the two directions in terms of time spent.

C. Effect of Location of Haptic Feedback and Number of Contacts

Our second and third questions asked where the stimuli should be applied, and whether one or two contact points should be used. Fig. 9 compares the average accuracy of users' responses for the dorsal, ventral, and both contact locations. Similar to Fig. 8, the data is shown for the total of all users, as well as split into two groups: users who performed very well during training, and others.

We performed a two-way ANOVA to analyze the data based on location and number of contact points. We found no statistical significance for the accuracy of any user groups. However, users with high training performance seem to spend significantly more time to complete the trials on average [F(2, 8) = 6.41, p = 0.0218], but we found no significance for neither users in total [F(2,22) = 0.37, p = 0.6952] nor [F(2,12) = 0.26, p = 0.7727].

D. Effect of Stiffness Level

We additionally investigated users' accuracy for different stiffness comparisons, without considering training performance. Fig. 10 shows that overall, users performed better using normal forces than skin stretch, although the statistically significant differences were observed only with the comparisons of 100 N/300 N (t(11) = 2.7080, p = 0.0204) and 500 N/300 N (t(11) = 3.0225, p = 0.0116)– cases where the differences between stiffness values were largest.

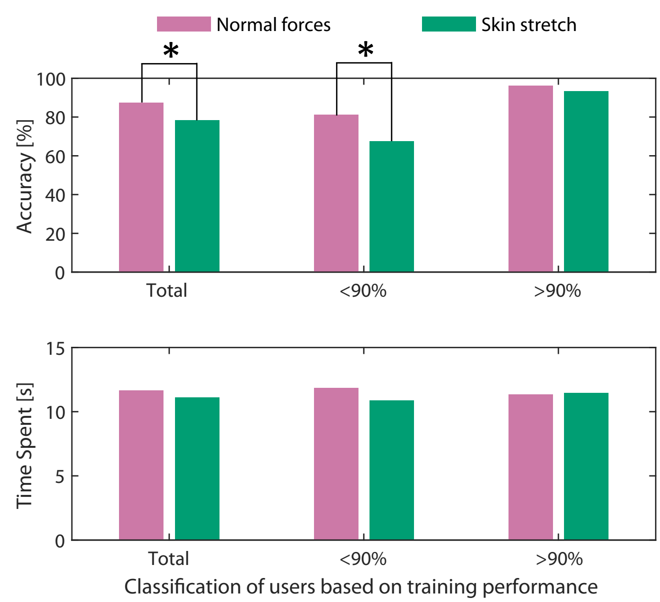


Fig. 8. Average accuracy of users' responses and average time users spent to complete each trial among all locations and stiffness comparisons. Overall, users performed significantly better with normal forces compared to skin stretch when asked to differentiate different stiffness values. A similar trend was observed for users with less than 90% accuracy during training, while for users with more than 90% accuracy during training, there was no significant difference. There was was no significant difference between the two directions in terms of time spent.

E. Survey Results

(Q1) the direction of forces they liked the most, (Q2) the direction of forces that was easiest to notice, (Q3) the location of forces they liked the most, and (Q4) the location of forces that was easiest to notice. The survey results are useful for understanding users' preferences. The first two questions asked about the direction of forces that users liked the most (Q1) and was easiest to notice (Q2). For Q1, 4 users chose skin stretch and 8 chose normal forces, although all users stated for Q2 that normal forces were much easier to notice. The verbal comments of the subjects are coherent with the analyses performed previously, so we can conclude that normal forces might be more effective than skin stretch for stiffness recognition.

The last two questions addressed the location of the stimulus. For Q3, the location of forces users liked the most, 1 user reported ventral side, 2 reported dorsal side, 5 reported both sides, and 3 reported that there was not much difference. On the other hand, when asked to evaluate the ease to notice the cues for (Q4), 3 users chose ventral side, 4 chose both sides, and 5 chose dorsal side. When we compared the average performance of these users, we found no correlation between the location they stated was easiest and the location for which they performed best.

These comments support the result that there is not a large difference between applying forces at a single contact point or two contact points. However, users did not agree about the best location of a single contact point.

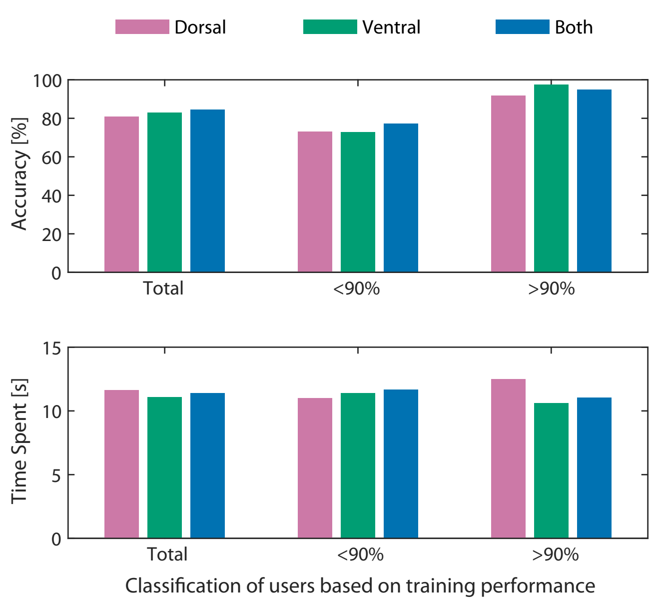


Fig. 9. Average accuracy of users' responses and average time users spent to complete each trial among all locations and stiffness values. Users with higher training performance had significantly better performance when forces were applied on the ventral side. These users also spent significantly more time to complete the trials when the stimulus was applied on the dorsal side. However, there was no significant difference when all users are evaluated together.

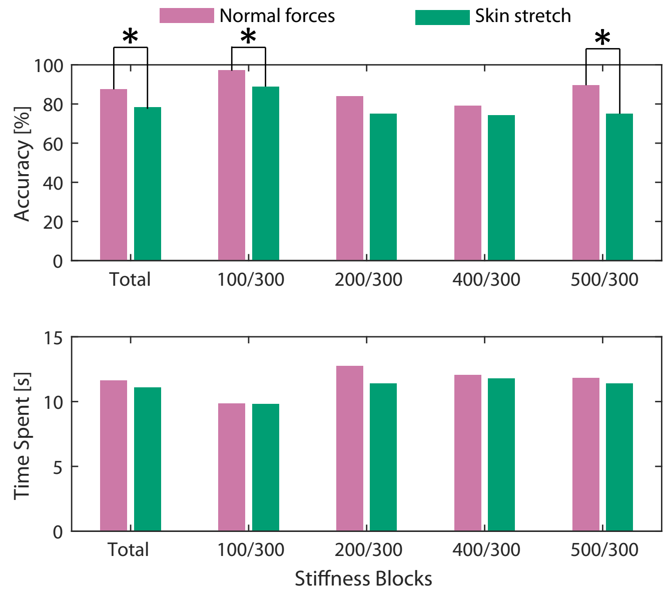


Fig. 10. Accuracy of users' answers and the time users spent for each trial among all locations: users perform significantly better with normal forces compared to skin stretch when asked to compare objects with highly different stiffness values, but not for objects with less different stiffness values. This might show that users are more sensitive to normal forces. Users also tend to spend more time completing the given task with normal forces, even though there was no significantly difference between skin stretch.

IV. Conclusion

In this work, we analyzed the effects of rendering interaction forces to user's forearm near the wrist based on virtual interactions.The results of our user study showed that normal forces help users differentiate different stiffness levels significantly better than skin stretch – especially when the difference between virtual object stiffness values are larger. Furthermore, users agreed that these haptic cues are easier to notice when applied in the normal direction.

Even though all users who participated in the study reported that haptic cues are easier to notice with normal forces, some reported that they enjoy skin stretch more because it was more "subtle and calm" compared to the normal forces. However, this may be due to larger forces being applied in the normal direction.

In future work, we will design a calibration phase to let each user decide the magnitudes of the haptic cues. We designed each haptic bracelet to apply interaction forces on the dorsal side, ventral side, and both sides near the wrist. The study results did not show any statistical significance among these locations. However, subjects tended to achieve better performance on the ventral side compared to the dorsal side, and similar performance between ventral side and both sides. The lack of significant differences was also supported with a verbal questionnaire. When asked to choose a location in which they could interpret haptic cues most easily, users gave a variety of answers.

It is also important to acknowledge that relocating the haptic feedback for active exploration tasks to another location requires a neurological mapping that subjects need to learn.

It is possible that the location is not that important as long as the forces are applied to user's skin in an effective manner. It is also possible that the best location to achieve haptic cues around the wrist is subjective. Future work could use alternative approaches to investigate the questions of location and number of contacts.

Finally, users are generally asked to interact with virtual environments using multiple fingers, instead of only the index finger. For this study, we simplified the task to the index finger to create a consistent, repeatable task. In the future, we will extend our analyses to two-finger grasping and identification of other mechanical properties using the lessons learned from this study.

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