Prefatory study of the effects of exploration dynamics on stiffness perception*

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***Abstract*— The utility of telerobotic systems is driven in large part by the quality of feedback they provide to the operator. While the dynamic interaction between a robot and the environment can often be sensed or modeled, the dynamic coupling at the human-robot interface is often overlooked. Improving dexterous manipulation through telerobots will require careful consideration of human haptic perception as it relates to human exploration dynamics at the telerobotic interface. In this manuscript, we use exploration velocity as a means of controlling the operator's exploration dynamics, and present results from two stiffness discrimination experiments designed to investigate the effects of exploration velocity on stiffness perception. The results indicate that stiffness percepts vary differently for different exploration velocities on an individual level, however, no consistent trends were found across all participants. These results suggest that exploration dynamics can affect the quality of haptic interactions through telerobotic interfaces, and also reflect the need to study the underlying mechanisms that cause our perception to vary with our choice of exploration strategy.**

I. INTRODUCTION

The Human body is capable of performing a wide variety of complex manipulation tasks requiring high dexterity, often with objects of different shapes, sizes and mechanical compliance. This ability is developed through years of practice in manipulating objects under varying conditions and in different environments [1]. Direct interaction with our environment relies heavily on force and tactile information from the environment [2]–[5], however, direct interaction is not always feasible. For environments that pose bodily harm, are located remotely, or are inappropriately scaled with respect to the body, telerobotic systems provide an excellent platform for exploration and manipulation.

However, at present, telerobots used in applications such as robotic surgery, prosthetics, and defense fail to render the rich haptic sensations akin to those perceivable in direct exploration of the environment. This is in large part due to the noise and limited capabilities of the sensors, actuators, and algorithms of the closed-loop systems [6]. Improvements in kinesthetic feedback to combat these limitations can often result in control instability [7], an area that has been addressed in literature using various methods, focused largely on modeling environmental uncertainties [8]. The majority of these methods, however, use simplified models of the operator's limb impedance, which fail to account for the their varying nature [9], [10].

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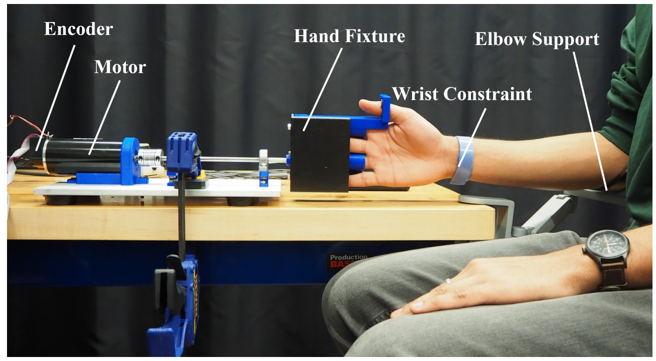

Fig. 1. Experimental setup with a motor, encoder, custom hand fixture, hook and loop wrist constraint, and the elbow support.

There is evidence to suggest that limb impedance informs human haptic perception [11]. Limb impedance can also change significantly with the motion of the upper limbs (exploration dynamics) [12], [13] and velocity and accuracy requirements of a task [14]. Performance in tasks like stiffness perception, which require integration of force and motion information (environmental impedance), can be affected by how humans integrate this information together [15], [16]. Thus, the interactions at the point of contact between the human and the robot can not be treated merely as sensory information exchange [17].

In the case of haptic interactions with the environment, forces exerted by the body have been shown to be regulated in terms of limb impedance [18]. Several studies have attributed our ability to modulate limb impedance in accordance with environmental parameters to the central nervous system (CNS). The most widely regarded theory holds that the CNS possesses an internal model of our limb impedance as well that of the environment, and uses sensory inputs to update the models appropriately [18]–[20]. Given that changes in limb impedance can often be attributed changes in exploration dynamics, it is essential to understand how well the CNS accounts for these changes in the development of environmental percepts.

However, we do not know how the CNS's modeling of our limb impedance due to varying limb dynamics informs our perception of the environemnt.

In this manuscript, we explore the relationship between exploration dynamics and haptic perception. We present an experimental haptic device that allows for single-DoF exploration of virtual environments in both task space and joint space. Using this experimental device, we investigated the effects of exploration dynamics on performance in a stiffness discrimination task. We controlled the exploration dynamics through modulation of exploration velocity. In an adaptive psychophysics paradigm, Just Noticeable Difference (JND) for stiffness was evaluated in two separate experiments for exploration of virtual torsion springs at 1) two predetermined velocities and 2) three user-specific exploration velocities based on each participant's preferred exploration strategy. In this way, we sought to evaluate perception for a predefined exploration strategy and one that was representative of the participants' natural exploration of their environment. Based on relationship between limb impedance and exploration dynamics discussed in literature, we hypothesized that exploration velocity has an effect on haptic perception.

In the following sections, we introduce our experimental setup and psychophysical methods common to both the experiments. This is followed by two sections including participant information, exploration parameters, metrics, statistical analysis and results for both experiments separately. We conclude with a discussion on these results in the broader context of effects of exploration dynamics on haptic perception.

II. Methods

This study consisted of two separate experimental investigations into the effect of exploration velocity on perception of stiffness. The first experiment utilized predefined exploration velocities and angular displacements. The second experiment utilized user-specific exploration velocities and angular displacements. The experiments were performed in different sessions taking place on different days and no participants performed both experiments. Both experiments used the same apparatus, same exploration velocity control method and the same psychophysical techniques as explained in the following sections.

A. Experimental Setup

The experimental apparatus consisted of a custom direct drive 1-DoF rotary kinesthetic haptic device (Fig. 1). A Quanser AMPAQ-L4 linear current amplifier was used to drive a Maxon RE50 motor (200 Watt), equipped with a Maxon HEDL 5540 encoder (3 channel, 500 CPT). A Quanser QPIDe PCI data acquisition card was used for data acquisition and controlled via a MATLAB/Simulink and Quarc real-time software interface at a sampling rate of 1 kHz. The study also involved collection of electromyogrpahy (EMG) data from five forearm and upper arm muscles, however EMG analysis is outside the scope of this manuscript.

A custom 3D printed hand fixture, attached via a rotary shaft, allowed for a unique alternating finger flexion/extension grip that was used to maintain a uniform grip across participants. Hook-and-loop straps were used to secure the fixture at the wrist to minimize flexion and extension, and radial and ulnar deviation of the wrist. The elbow was placed on a height adjustable support to align the forearm's axis of rotation with the device's rotational axis.

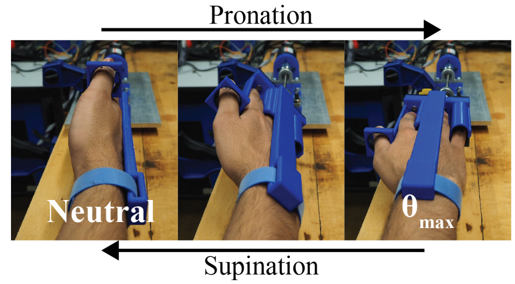

Fig. 2. Exploration protocol followed by the participants to perceive the virtual springs.

B. Procedure

All participants were consented according to a protocol approved by the Johns Hopkins School of Medicine Institutional Review Board (Study #IRB00148746), and were compensated at a rate of $10 per hour. After giving informed consent, participants were seated on a height adjustable chair next to the kinesthetic device. The participants were instructed to adjust their seat height and posture to maintain elbow flexion at 90 degrees and have no upper arm abduction. The participants then inserted their right hand into the fixture and the experimenter secured it in place with a hook and loop strap. The elbow support was adjusted such that it only made contact at the Olecranon (tip of the elbow).

C. Exploration Velocity Control

Each exploration required pronation of the forearm from the neutral position to the maximum angular displacement position θ_{max} and supination back to normal (as shown in Fig. 2). A metronome and an LED were used to assist the participant in maintaining the required velocity V. The participants began their pronation from the neutral position at the first beat, pronated until they reached the specified maximum displacement, syncing it with the second metronome beat, and supinated back to reach the neutral position at the third beat. An LED was programmed to light up when the participants were within 2.5 degrees of the neutral and maximum displacement position θ_{max}, to alert participants that they had reached the target position. The 2.5 degrees margin was selected based on pilot experiments and takes into account the amount of time it takes participants to notice the LED and either switch their direction of rotation or stop. The metronome frequency f_m was set in beats per minute (BPM) using the following equation:

$$f_m = \frac{60 \cdot V}{\theta_{max}} \quad (1)$$

D. JND Estimation

A simple two-interval forced choice (2IFC) same/different task was used to estimate each participant's JND for different experimental conditions. The JND for each condition was obtained in a single session. The conditions were tested for in consecutive sessions separated by a five minute break. A weighted 1 up/3 down staircase algorithm was used to determine the JNDs. Based on values suggested in [21], the

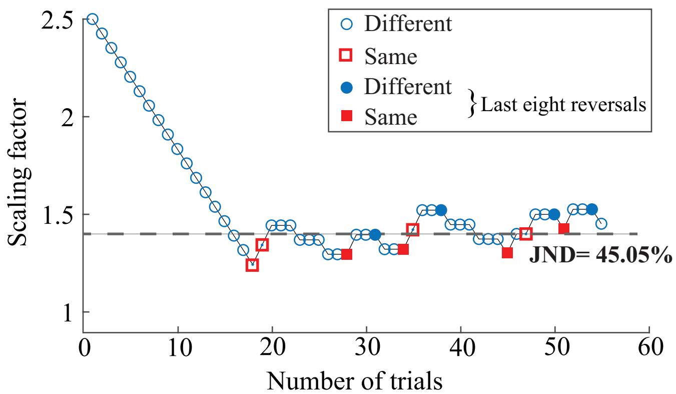

Fig. 3. Sample staircase for a representative participant performing active exploration at 67.5 deg/s

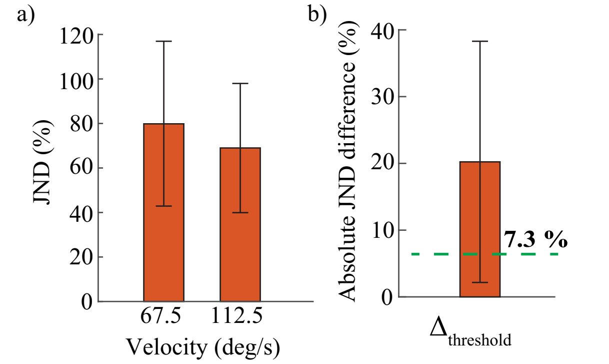

Fig. 4. a) JNDs obtained at the two exploration velocities in experiment 1 and b) descriptive figure for the one-sample t-test comparing $\Delta_{threshold}$ to 7.3%. Error bars represent one standard deviation.

up step-size was set at 10% of the reference stimuli and the ratio of down step-size and up step-size was 0.73 for a proportion correct target of 83.15%. The spring torque was rendered according to the following relationship:

$$\tau = s \cdot k \cdot \theta \qquad (2)$$

where k is the spring constant, $s \in [1, 2.5]$ is a scaling factor whose value is determined by the staircase algorithm, and θ is the angular displacement of the participant's forearm with respect to the neutral position.

The reference torsion spring was set at 1.5 mNm/deg and the staircase was initialized at a value 2.5 times higher than the reference stimuli. The staircase terminated after ten reversals and the average of the last eight reversals was used to determine the stiffness discrimination threshold. A "1 up/ 1 down" approach was followed until the first reversal. If the participant missed the target position by more than 2.5 degrees or failed to sync their motion with the metronome beats for any of the two springs, the trial was deemed as unsuccessful. These trials were repeated before moving ahead on the staircase. Participants were informed to treat repetitions as a fresh trial and the springs were repeated as a pair in a random order. Additionally, five catch trials were presented to each participant, where the same reference spring was presented twice. If the participant reported more than one of these trials incorrectly (Different), the experiment was terminated and the participant's data was excluded from the final analysis.

III. Experiment 1: Fixed exploration strategy

A. Participants

We investigated the ability of n=10 individuals (7 male, 3 female, age = 24±6 years) to distinguish virtual torsional springs at two different predetermined angular velocities of exploration. The duration of the experiment was approximately 90 minutes.

B. Exploration Parameters

The experimental protocol consisted of a psychophysical test to determine the JND for the reference torsion spring at two different exploration velocities, 67.5 deg/s and 112.5 deg/s. These velocities were chosen based on results from pilot experiments so that participants could consistently follow the task instructions. The staircase algorithm was used to evaluate JNDs at the two velocities in two separate sessions in a randomized order. For both the sessions, θ_{max} in Eq. 1 was set to 90 degrees.

C. Metrics

The JNDs at both the exploration velocities were used as a quantitative measure of the participant's perception. The absolute difference in JND for both velocities, 67.5 deg/s ($\mathrm{JND}_{67.5}$) and 112.5 deg/s ($\mathrm{JND}_{112.5}$), was also calculated for each participant as $\Delta_{threshold}$ as shown below.

$$\Delta_{threshold} = |\mathrm{JND}_{67.5} - \mathrm{JND}_{112.5}| \qquad (3)$$

D. Statistical Analysis

Statistical analyses were performed in MATLAB R2018b. The data was tested for outliers, defined as values outside 1.5 times the inter-quartile range for the respective variables. Assumptions of normality were tested using Shapiro Wilk test, when required. A pairwise t-test was used to compare the $\mathrm{JND}_{67.5}$ and $\mathrm{JND}_{112.5}$ values of all participants. A one tailed, one sample t-test was performed to compare $\Delta_{threshold}$ of all participants to 7.3%, which represents the minimum step-size of our staircase algorithm, and thereby serves as a proxy measurement for the resolution at which we can estimate the JND using our experimental protocol.

E. Results

The results of JND experiments are shown in Fig. 4. The assumption of normality was met for the $\mathrm{JND}_{67.5}$, $\mathrm{JND}_{112.5}$, and $\Delta_{threshold}$ values based on the results of the Shapiro Wilk test ($p>0.05$). The pairwise t-test revealed no significant difference between $\mathrm{JND}_{67.5}$ and $\mathrm{JND}_{112.5}$ ($p>0.05$). Based on the one-sample, one tailed t-test, $\Delta_{threshold}$ was found to be statistically greater than 7.3% ($p<0.05$).

IV. Experiment 2: Participant-specific Exploration Strategy

A. Participants

We investigated the ability of n=13 individuals (10 male, 3 female, age = 26±3 years) to distinguish virtual torsional springs at three different angular velocities of exploration. The duration of the experiment was approximately 90 minutes.

B. Exploration Parameters

A calibration session was performed prior to the start of the experiment, where each participant explored the reference torsion spring with their preferred velocity and displacement in order to obtain user-defined estimates of V_p and θ_{max} from Eq. 1. Participants were asked to explore the virtual torsion spring by pronating (counter-clockwise rotation) then supinating (clockwise rotation) their forearm, avoiding any jerks in their motion, for a total of ten explorations. No restrictions were placed on the magnitude and velocity of their exploration. The second through ninth exploration were used to determine the average maximum angular displacement θ_{max} and preferred exploration velocity V_p for each participant.

The experimental protocol consisted of a psychophysical test to determine the JND for the reference torsion spring at three different velocities, which were specific to each participant. The velocities were based on each participant's preferred exploration velocity and were set at three levels: *Low* (V_p - 15 deg/s), *Preferred* (V_p) and *High* (V_p + 15 deg/s). The 15 deg/s windows was chosen based on pilot experiments to ensure that participants could consistently follow the task instructions. Unlike the first experiment, where maximum displacement was fixed at 90 degrees, the maximum displacement for this experiment was set at each participant's average maximum angular displacement θ_{max}.

C. Metrics

JNDs were obtained for all participants for the three velocities: *low* (JND$_{low}$), *preferred* (JND$_{pref}$), and *high* (JND$_{high}$). The absolute values of pairwise differences in JNDs were calculated for each participant as shown below.

$$\Delta_{lp} = |\text{JND}_{low} - \text{JND}_{pref}| \tag{4}$$

$$\Delta_{ph} = |\text{JND}_{pref} - \text{JND}_{high}| \tag{5}$$

$$\Delta_{hl} = |\text{JND}_{high} - \text{JND}_{low}| \tag{6}$$

We evaluated the coefficient of variation for exploration velocity and maximum angular displacement of the calibration trials for each participant. The mean values of c_v and c_θ were calculated as shown below.

$$c_v = \frac{\sum_{i=1}^{n}\left(\frac{V_{sd_i}}{V_{p_i}}\right)}{n} \tag{7}$$

where V_{sd_i} and V_{p_i} are the standard deviation and average exploration velocity, respectively for the second through ninth calibration trials of each individual participant, and n represents the total number of participants.

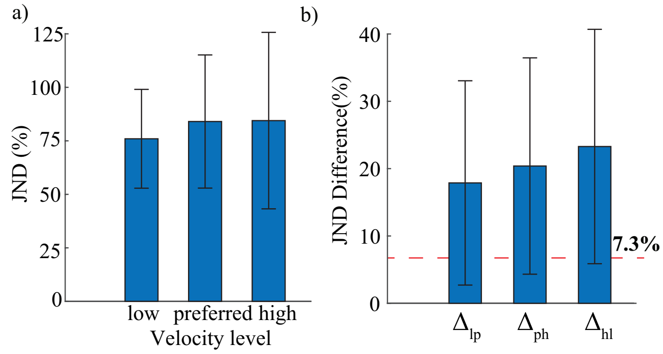

Fig. 5. a) JNDs obtained at the three exploration velocities in experiment 2 and b) descriptive figure for the one-sample t-test comparing Δ_{lp},Δ_{ph} and Δ_{hl} to 7.3% respectively. Error bars represent one standard deviation.

$$c_\theta = \frac{\sum_{i=1}^{n}\left(\frac{\theta_{sd_i}}{\theta_{max_i}}\right)}{n} \tag{8}$$

where θ_{sd_i} and θ_{max_i} are the standard deviation and average maximum angular displacement, respectively for the second through ninth calibration trials for each individual participant, and n represents the total number of participants.

Statistical analyses were performed in MATLAB R2018b and IBM SPSS 26. The data was tested for outliers as defined in the previous experiment (1.5 times the interquartile range). The Shapiro-Wilk test was used to check for normality and Mauchly's test was used to check for sphericity, where appropriate. A repeated measures ANOVA was used to evaluate effects of velocity level on JND. One tailed, one sample t-tests were performed to compare Δ_{lp}, Δ_{ph} and Δ_{hl} of all participants to 7.3%, as appropriate. Two one-tailed paired t-tests were performed to check if Δ_{hl} was greater than Δ_{lp} and Δ_{ph}, respectively.

D. Results

The statistical analysis was limited to nine out of the thirteen participants. Two participants failed to meet the criteria of smooth exploratory motion (avoiding jerks) for the calibration session. In order to remain consistent with our aim to estimate participants' preferred exploration strategies, we elected to terminate the experiment as opposed to giving additional instructions that could influence their natural exploration strategy. One participant failed more than one catch trials in a single JND session and their experiment was terminated early. For one participant, the experiment was terminated due to hardware malfunction.

The results of the JND experiment are shown in Fig. 5 for the three different exploration velocity levels. Shapiro-Wilk test confirmed that the JND data for all three conditions satisfied the assumptions of normality ($p>0.05$) and they also satisfied the assumption of sphericity based on Mauchly's Test of Sphericity ($p>0.05$). Using a repeated

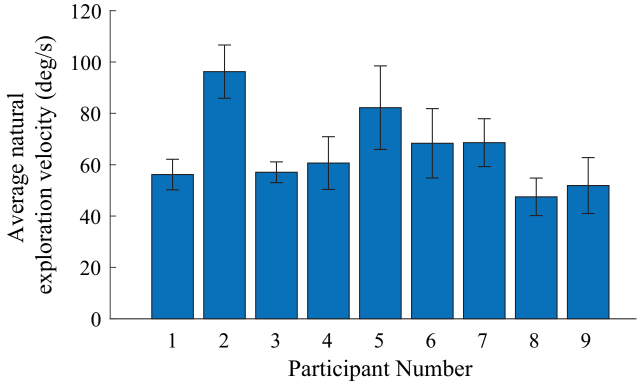

Fig. 6. Average natural exploration velocity (V_n) for each participant measured during calibration of experiment 2. Error bars represent one standard deviation.

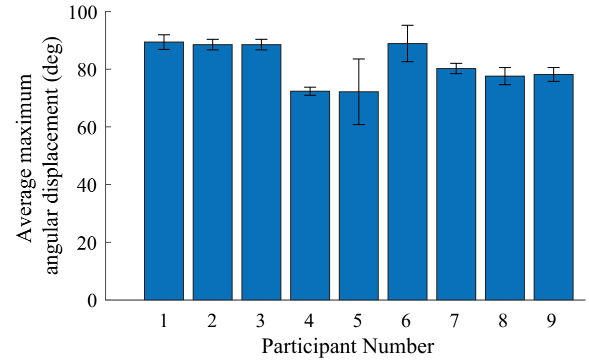

Fig. 7. Average maximum angular displacement (θ_{max}) for each participant measured during calibration phase of experiment 2. Error bars represent one standard deviation.

measures ANOVA we found no statistically significant effect of exploration velocity on JND (F(2,16)=0.595, p>0.05).

One outlier was identified in the Δ_{lp} results and not included in the following analysis. Shapiro-Wilk test confirmed the assumption of normality for the Δ_{lp}, Δ_{ph} and Δ_{hl} distributions (p>0.05). Subsequent one sample, one tailed t-tests confirmed that all three parameters, Δ_{lp}, Δ_{ph} and Δ_{hl} were significantly greater than 7.3% (p<0.05). The paired t-tests comparing Δ_{hl} to Δ_{lp} and Δ_{ph} revealed no statistically significant differences (p>0.05).

Participants maintained a high consistency in velocity and displacement for their calibration trials. The mean coefficient of variation for exploration velocity (c_V) and maximum angular displacement (c_θ) were 0.15 and 0.05 respectively. Fig. 6 highlights the exploration velocity for each participant from the calibration session and Fig. 7 highlights the corresponding maximum angular displacement.

V. Discussion

In this study, we performed two preliminary experiments to begin understanding the effects of haptic exploration dynamics on performance in perception oriented tasks, a particularly understudied area of investigation. The dynamics of haptic exploration are a particularly interesting topic of investigation due to evidence that suggests that acceleration and velocity of joints in the upper limbs are shown to have significant effects on limb impedance [12]; in particular, the stiffness of our limbs changes with our exploration dynamics [13]. It is not clear, however, what effect, if any, these changes in limb impedance have on our perception.

While the results presented above provide insights into the effects of exploration velocity on stiffness perception, it is worth noting that the JND values obtained in these experiments were higher than those previously reported in literature [16] for stiffness perception. We believe this likely results from an interplay of two primary factors: 1) limiting participants to a single exploration of each spring in the perceptual task, and 2) the additional cognitive effort required from the participant to pay attention to audio and visual cues in order to maintain the required exploration parameters.

While we acknowledge that our methods may have inflated the perceptual thresholds, the use of audio and visual cues were integral in enabling exploration velocity control. Likewise, while both single and multiple explorations have been used in literature [16], [22], we chose the former given the length of our study and the need for consistent velocities for our measurements. Still, we believe that despite the higher JND values, the consistency of our methodology across all participants, for all conditions and for both experiments, validates our within-subjects findings discussed below.

We observed that, on an individual basis, JNDs for stiffness perception were significantly different for different exploration velocities. This is in line with the literature on motor performance and limb impedance, which suggests that exploration dynamics can have an effect on our limb impedance and therefore, our perception of the environment [12], [13], [18]. However, no significant preference for a particular velocity was observed in our sample for both experiments. The step-size was chosen as a point of comparison since any difference larger than this value should be indicative of a difference in participants' perception and not a by-product of the resolution of measurement method. The step-size acted as a rather conservative estimate of our resolution in measuring thresholds. In practice, the staircase can capture perceptual differences smaller than the step size, given the manner in which the staircase is weighted and the averaging of reversals to obtain the final JND.

In the second experiment, we opted to evaluate JNDs at three velocities to determine if perceptual sensitivity either increases or decreases linearly with increasing exploration velocity. For the participants to be consistently better at either high or low velocities, Δ_{hl} should be significantly greater than Δ_{lp} and Δ_{ph}, placing JND$_{pref}$ in between JND$_{low}$ and JND$_{high}$. We found no evidence that participants were consistently better at higher or lower velocities.

We believe that these results reflect a gap in our understanding of the internal models of our body dynamics formed by the CNS. Additional experiments will be required to understand the fidelity of these internal models and how they are incorporated by our CNS while forming a percept of external stimuli.

The consistency of JND values across both experiments, helps ensure that the results from our first experiment were not merely a reflection of our choice of the fixed velocities. It is also worth highlighting here that in our calibration phase for the second experiment, we found that participants were consistent with the velocity and angular displacement for their preferred exploration strategy, despite receiving no explicit instructions to do so. We believe that the existence of a preferred consistent exploration strategy can be leveraged to perform similar experiments, with simpler cues that enable participants to concentrate more heavily on the haptic feedback in the future.

VI. Conclusion

Our results indicate that exploration velocity may have an effect on stiffness perception, however, that effect appears to vary on an individual basis. While the effects of exploration velocity may not be consistent across participants, or within participants at different velocities, the existence of perceptual differences based on exploration dynamics is an important finding that can inform our design of haptic feedback devices in the future. As we look to create more stable and transparent telerobotic systems, it will be essential to consider how human haptic perception varies with the exploration dynamics to enable dexterous manipulation of our environments through telerobots. Equally important, is the need to dissect this phenomenon further and understand the underlying mechanisms that bring about these changes in perception, as they relate to our own body dynamics.

Acknowledgment

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