Effects of Latency and Refresh Rate on Force Perception via Sensory Substitution by Force-Controlled Skin Deformation Feedback

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Abstract—**Latency and refresh rate are known to adversely affect human force perception in bilateral teleoperators and virtual environments using kinesthetic force feedback, motivating the use of sensory substitution of force. The purpose of this study is to quantify the effects of latency and refresh rate on force perception using sensory substitution by skin deformation feedback. A force-controlled skin deformation feedback device was attached to a 3-degree-of-freedom kinesthetic force feedback device used for position tracking and gravity support. A human participant study was conducted to determine the effects of latency and refresh rate on perceived stiffness and damping with skin deformation feedback. Participants compared two virtual objects: a comparison object with stiffness or damping that could be tuned by the participant, and a reference object with either added latency or reduced refresh rate. Participants modified the stiffness or damping of the tunable object until it resembled the stiffness or damping of the reference object. We found that added latency and reduced refresh rate both increased perceived stiffness but had no effect on perceived damping. Specifically, participants felt significantly different stiffness when the latency exceeded 300 ms and the refresh rate dropped below 16.6 Hz. The impact of latency and refresh rate on force perception via skin deformation feedback was significantly less than what has been previously shown for kinesthetic force feedback.**

I. INTRODUCTION

Time delay poses a major obstacle in applications of haptic (force and touch) feedback, such as telerobotic surgeries and virtual training, due to stability concerns [1], [2]. It is well known in bilateral telerobotic systems that transparency and stability are competing design goals [3]. As a result, using kinesthetic force feedback systems in the presence of time delay limits the realism of the haptic feedback. Sensory substitution, the process of providing feedback through a different sense than what is naturally used, has replaced force with sound [4], vision [5], and vibrations [6]. This eliminates the transparency versus stability trade-off, but at the cost of eliminating transparency entirely.

By providing sensory substitution through skin deformation, some of the realism of haptic feedback can be maintained. This approach has been referred to as “sensory subtraction” because it removes the kinesthetic component of haptic interaction while maintaining the tactile component [7], [8]. In contrast to a traditional kinesthetic haptic device, which applies forces or torques across the user’s movable joints during interaction with a haptically rendered object, a skin deformation device applies a tangential (lateral) and/or normal force to the skin, typically at the fingerpad.

Most skin deformation devices use a position-based control system that deforms the skin a select distance based on the desired magnitude of force feedback, necessitating assumptions about the stiffness of the skin and/or manual tuning. Here we use instead a force-controlled skin deformation device that directly controls the force that deforms the skin [10]. While prior work has examined force perception using a displacement-based skin deformation device [11], force perception using a force-controlled skin deformation device requires further study.

The main goal of this work is to understand the effects of latency and refresh rate on human perception of haptic feedback via skin deformation. Prior research on these relationships exists for kinesthetic haptic devices [12], [13], [15] but not skin deformation devices. In addition, prior work compares the effectiveness of skin deformation devices to kinesthetic haptic devices without considering time delay [10], [11].

We performed a study to quantify the effects of added latency and reduced refresh rate on perceived stiffness and perceived viscous damping in a haptic virtual environment. The results show the potential for skin deformation feedback to replace force feedback for low-cost embedded systems that have poor latency and refresh rate, as well as in teleoperation systems with time delay, by maintaining realism while avoiding some of the stability problems associated with kinesthetic force feedback.

II. BACKGROUND

A. Latency and Refresh Rate

Latency and refresh rate both refer to time delays in systems, but each manifests differently. In a standard kinesthetic force-feedback haptic system for virtual reality or teleoperation, a human operator moves the end-effector of the haptic device, which records its position. The end-effector is represented by a haptic interaction point in the virtual or remote environment. Force feedback is typically calculated based on the relative position and velocity of the haptic interaction point and objects in the environment. The actuators of the haptic device generate this force, and the movement of the human operator is consequently affected. Latency and refresh rate insert time delays at different points in this loop.

Latency is a time delay associated with the transfer of information between the haptic device and the computer. For example, during bilateral teleoperation of a robot in space from earth, the haptic device on earth continuously streams data to the robot, and the robot continuously streams data to the haptic device. Due to the large distance and thus time delay associated with data transfer, both the robot and the human operator receive position and/or force data after a delay on the order of milliseconds. In this study, rather than directly send force data to the haptic device, we simulated latency by first

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storing force data for a short time before transmitting it. Effectively, this creates delayed but continuous haptic force feedback.

Refresh rate is the frequency at which a computer is capable of doing calculations, such as computing the force to be rendered in a virtual environment. For example, a surgical simulator may take significant time to update a deformable model, slowing the refresh rate of the simulation. In this study, a decrease in refresh rate was achieved by introducing a hold within the haptic feedback control loop. Rather than immediately calculating and sending an updated force value for the haptic device after receiving new position information, the computer holds and transmits the old force value for a short duration. This effectively reduces the haptic device's refresh rate. Unlike the latency simulation, where force data is sent continuously after a delay, the refresh rate simulation reduces the continuity of the feedback.

B. *Force Perception in Kinesthetic Force Feedback*

Prior research on the effect of time delay on kinesthetic force feedback has two main results relevant to our study. First, added latencies (on the order of 50 ms) or decreased refresh rates (on the order of 10 Hz) can drastically destabilize kinesthetic haptic force feedback [12], [13], [19]. Second, the relationship between latency and refresh rate and perceived stiffness has been measured for haptic devices. In kinesthetic haptic devices, added latency was not correlated with perceived stiffness but was negatively correlated with perceived damping [14], [15], [16]. In contrast, reduced refresh rate has been correlated with a decrease in perceived stiffness while the relationship between reduced refresh rate and perceived damping is not well documented [17], [18], [19].

C. *Skin Deformation Feedback*

Here we use force-controlled skin deformation, in contrast to typical devices that are based on displacement of the skin. Position-controlled skin deformation devices displace the skin a distance corresponding to the force desired to represent the interaction with virtual environments. Instead, the device used in our study sends the force information directly to the skin deformation device. This approach gives the operator an accurate force display despite unknown skin stiffness [10].

III. SKIN DEFORMATION DEVICE DESIGN AND CONTROL

A. *Mechanical Design*

This study used a skin deformation device attached to the end-effector of a commercially available 3-DoF kinesthetic haptic device, the Force Dimension Omega.3 (Fig. 1). The Omega.3 provided information on the user's position and only provided force to compensate for the weight of the skin deformation device. The skin deformation device uses a 3-DoF delta mechanism to provide tangential and normal force directly to the fingerpads of the thumb and index finger. The device uses three Maxon DCX16S DC motors with 6:6:1 gearboxes and 1024 count per revolutions optical encoders. An OPTOFORCE OMD-20-FG-100N is attached to the end-effector of the delta mechanism for 3-axis force sensing with a 15Hz bandwidth. Additionally, a Phidgets 5 kg micro load cell mounted on the force sensor measures the grip force of the subject on the device. For skin deformation feedback, a 20 mm square aperture is attached to the base of the device to allow the user to squeeze the index finger and thumb onto the device. The tactor under each finger contacts the user's skin and applies skin deformation feedback localized to the fingerpad.

B. *Control System*

The force-feedback control system used the Robotic Systems Integration RMP EtherCAT. Advanced Motion Controls DZEANTU-020B080-2A motor drivers for the EtherCAT regulated motor currents using PD control. The force sensor data and the motor current were updated at a rate of approximately 1 kHz by the EtherCAT system with a nominal latency of 1 ms. CHAI3D was used to render the virtual environment. Interaction forces were computed from the user's position measured by the Omega.3. Desired motor torques for the skin deformation device were calculated from the desired force of the end-effector through the forward kinematics of the delta mechanism, and then translated into motor currents. Motor optical encoders measured the joint angles for each of the joints in the delta mechanism. The force output by the end-effector of the skin deformation device was measured by the 3-axis force sensor. PID control was used to control the force of the tactile device end-effector.

IV. EXPERIMENT DESIGN

A. *General Procedures*

A total of 13 people (8 female, 5 male) participated in this experiment. All subjects gave informed consent, and the protocol was approved by the Stanford University Institutional Review Board.

The experiment consisted of four parts given in random order. These four main parts tested the effects of latency and

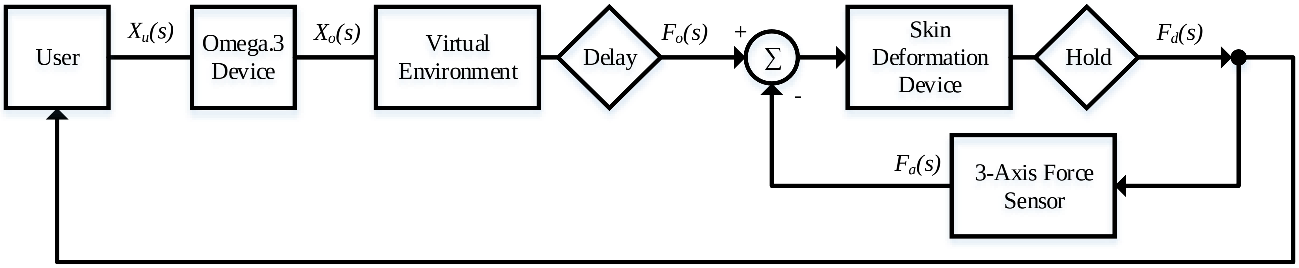

Fig. 1. Block diagram illustration of latency and refresh rate simulation. The user would control the Omega.3 device which would send position information to the virtual haptic environment. The force values from the environment would then be sent into a haptic feedback loop for the skin deformation device. If latency was being tested, the forcing values from the virtual environment would be delayed before being sent to the haptic feedback loop. If refresh rate was being tested, the force output from the haptic feedback loop would be held for a short duration before being updated.

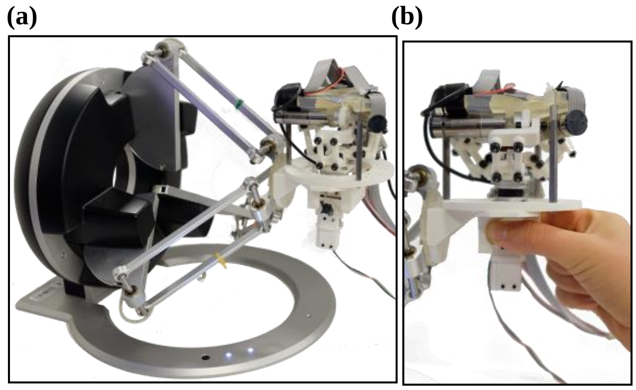

Fig. 2. (a) A 3-degree-of-freedom kinesthetic force feedback device (Omega.3) supports the skin deformation haptic device. The Omega.3 tracks the position of the end effector, while the skin deformation haptic device provides force feedback to the operator. (b) A 3-degree-of-freedom force-controlled skin deformation haptic device is held by a human operator. The operator grips the device around the aperture to prevent movement of the fingers, and the black tactors provide skin deformation feedback.

refresh rate on perceived stiffness and perceived viscous damping. Each part included training – time for the subject to accustom themselves to the device and the task when no latency or refresh rate change was simulated. This was then followed by a total of six randomized trials. The entire experiment was composed of twenty-four total trials.

Latency and refresh rate were both implemented as time additions to different parts of the control program. Latency was simulated by adding a time delay before force feedback information was sent to the skin deformation device. The force feedback information was continuous, but delayed. Refresh rate was simulated by adding a hold after the calculation of the force feedback. The program would send this held forcing information to the skin deformation device for a short duration and only afterwards recalculate new forcing information. These delay implementations were the same for the stiffness and the damping tests.

Graphics on the computer screen provided information about the test and visually displayed the virtual environment (Fig. 3). Text displayed the trial number, messages indicating whether the subject had increased the stiffness or viscous damping of the subject-controlled object, and warnings when a subject reached the upper or lower limit of the adjustable range. Participants were seated at a desk in front of this graphical display such that their torso was about 30 to 40 cm from the display and the device. With their right hand, the participant grasped the skin deformation device. With their left hand, participants used three keys on a standard keyboard to increase or decrease the property that was being tested (either stiffness or viscous damping) or to advance to the next trial. Graphics displayed a two-dimensional haptic environment, and the three-dimensional haptic device was constrained to move in the plane of that environment. The position of the Omega.3 was shown as a ball (haptic interaction point) in the graphical display.

B. *Stiffness Test*

In the stiffness test, participants viewed three rectangles on the two-dimensional graphic display: a left rectangle with tunable stiffness (blue), a right rectangle with reference stiffness (gray), and a larger rectangle with no stiffness (red) that served only to visually occlude the tops of the other rectangles. The larger rectangle had no material properties and did not impart any forces. The only purpose of this larger rectangle was to prevent the subject from seeing the movement of the haptic interaction point during interaction to eliminate the influence of visual stimulation. Yet, the subjects could see their cursor moving in and out of the areas behind the large rectangle, allowing the subjects to have a general idea of the location of their cursor to they could verify that they were exploring a particular part of the vistual environment.

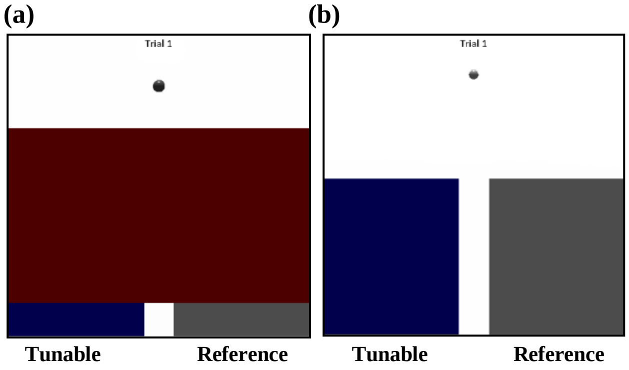

Fig. 3. Graphic displays presented to the participants during the study. Both tests included left and right rectangles, representing objects with tunable and reference stiffnesses, respectively. (a) Display for the stiffness test. The stiffness test included a third rectangle that occluded the point of contact between the ball and the stiffness rectangles. (b) Display for the viscous damping test.

The left (tunable) rectangle stiffness was modified in increments of 10 N/m (with a minimum stiffness of 0 N/m and a maximum stiffness of 300 N/m) by the subject using keyboard presses, and the right (reference) rectangle had a single reference stiffness of 150 N/m. This reference rectangle had an added latency or reduced refresh rate effect that varied from trial to trial. The participant was able to touch the left or right rectangles and feel their stiffness. The participant was asked to tune the stiffness of the left rectangle as closely as possible to the stiffness of the right rectangle. The participant then pressed a key on the keyboard to record the tuned stiffness, and moved on to the next trial in the experiment. There were a total of twelve stiffness trials (six for latency and stiffness and six for refresh rate and stiffness).

C. *Viscous Damping Test*

The viscous damping test resembled the stiffness test, except that there was no third rectangle – the participants' haptic interaction point would move through and be hidden by the first two rectangles during the damping tests, making the additional visual obstruction provided by the third rectangle redundant. The participant compared the viscous damping of the left (tunable) and right (reference) rectangles. The participant tuned the viscous damping of the left (tunable) rectangle using keyboard presses, in increments of 0.5 Ns/mm (with a minimum of 0 Ns/mm and a maximum of 10 Ns/mm). The right (reference) rectangle had a single reference damping at 5 Ns/m. The set of latencies and refresh rates used were the same as in the stiffness test. After the participant tuned the damping, a keyboard press recorded the participant's tuned damping, and then the test proceeded to the next trial. There were a total of twelve trials (six for latency and damping and six for refresh rate and damping).

V. RESULTS

A. *Latency Tests*

The nominal latency of the system (1 ms) was negligible in comparison to the added latency, so the following results refer only to the added latency.

Figure 4(a) shows participants' individual tuned stiffness and the group average for a 150 N/m reference stiffness with added latencies. The group averages and 95% confidence intervals for these added latencies, from 0 to 500 ms in 100 ms increments, were (in N/m): 125 (95% conf. int. 14), 132 (22), 146 (31), 204 (38), 182 (43), and 214 (39). These large confidence intervals were expected, because tactile perception varies widely between subjects and can also be affected by trial order. Therefore, we also performed an

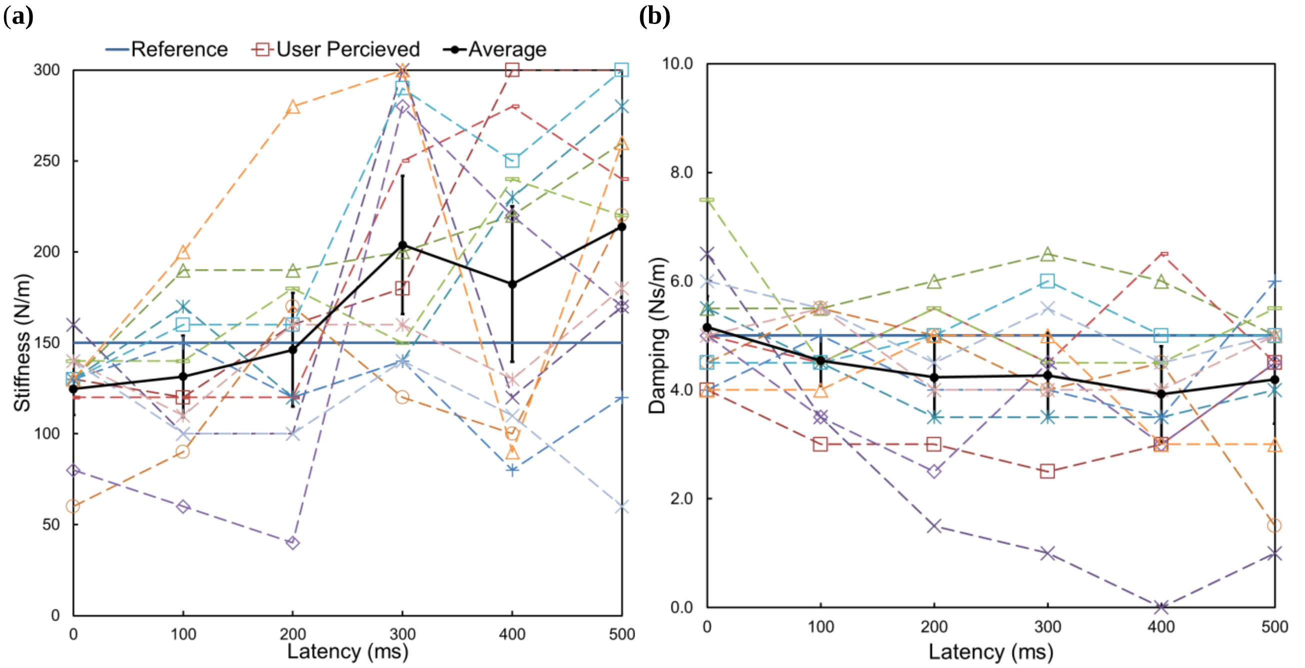

Fig. 4. Effects of latency on (a) stiffness and (b) damping for skin deformation feedback. 95% confidence intervals are plotted for average perceived values. The average results indicate that participants perceived increased stiffness with added latency, but perceived damping was not significantly influenced by added latency.

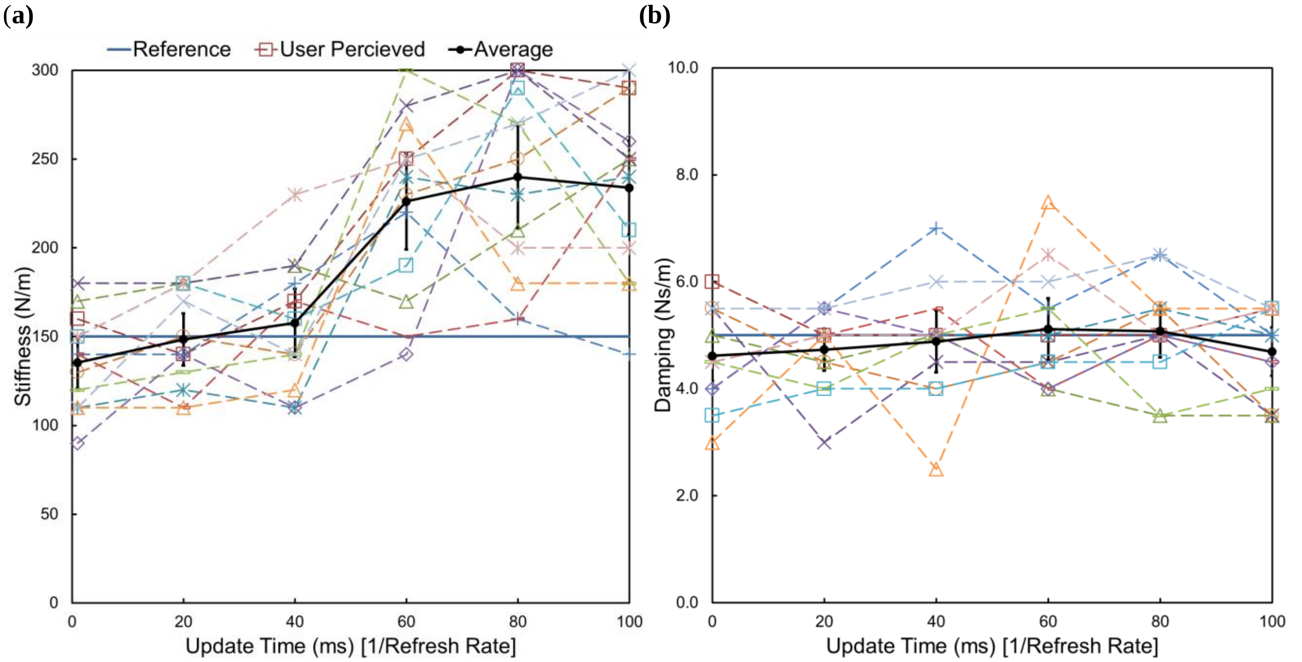

Fig. 5. Effects of update time (1/refresh rate) on (a) stiffness and (b) damping for skin deformation feedback. 95% confidence intervals are plotted for average perceived values. The average results indicate that participants perceived increased stiffness with increased update time (reduced refresh rate), but perceived damping was not significantly influenced by update time (or refresh rate).

ANOVA to determine if any of the changes in stiffness with added latency were statistically significant at the 0.05 level. The data for 0 and 100 ms are statistically significantly different from the data for 300 and 500 ms while the data for 200 and 400 ms are not statistically different from any other group. Additionally, there was no statistically significant difference between 0 and 100 ms, nor was there a statistically significant difference between 300 and 500 ms.

Figure 4(b) shows participants' individual tuned damping and the group average for a 5 Ns/m reference damping with added latencies. For the same range of added latencies as in the stiffness test, the group averages and 95% confidence intervals were (in Ns/m): 5.2 (95% conf. int. 0.6), 4.5 (0.5), 4.2 (0.7), 4.3 (0.8), 3.9 (0.9), and 4.2 (0.8). ANOVA found no statistically significant differences at the 0.05 level in damping perception with increased latency.

B. *Refresh Rate Tests*

The nominal refresh rate in the system was approximately 1 kHz, which corresponds to a 1 ms update time. This becomes negligible as this delay is increased toward 100 ms. Refresh rate tests ranged from 0 to 100 ms of added update time, or from 1 to 10 Hz refresh rate.

Figure 5 shows participants' tuned stiffness and damping values versus update time (the reciprocal of refresh rate) in ms. Update time was used to maintain consistent units among the four plots in Figures 3 and 4 to facilitate comparison.

Figure 5(a) shows participants' individual tuned stiffness and the group average for a 150 N/m reference stiffness with added update time. The group averages and 95% confidence intervals for these added update times, from 0 to 100 ms in 20 ms increments, were (in N/m): 135 (95% conf. int. 14), 148 (15), 158 (19), 226 (27), 240 (29), and 234 (27). ANOVA for stiffness perception for added update times of 0, 20, and 40 ms were all statistically significantly different at the 0.05 level from those of 60, 80, and 100 ms. This analysis also found no statistically significant difference at the 0.05 level between added update times of 0, 20, and 40 ms or between the added update times of 60, 80, and 100 ms.

Figure 5(b) shows participants' individual tuned damping and the group average for a 5 Ns/m reference damping with added latencies. For the same range of added latencies as in the stiffness test, the group averages and 95% confidence intervals were (in Ns/m): 4.6 (95% conf. int. 0.5), 4.7 (0.4), 4.9 (0.6), 5.1 (0.6), 5.1 (0.5), and 4.7 (0.5). ANOVA found no statistically significant differences at the 0.05 level in damping perception with increased update time.

VI. DISCUSSION

Results from the study suggest that the relationship between latency and refresh rate with perception of stiffness and viscous damping is not the same for force-controlled skin deformation devices and kinesthetic devices. For skin deformation, perceived stiffness rises with added latency or added update time (decreased refresh rate) and there is no change in the perception of viscous damping in response to either latency and update time (refresh rate) changes. Qualitatively, participants would comment on but did not seem to have difficulty completing tests, which suggests the change in stiffness perception and the constant damping perception to be directly a result of changing latency and refresh rate. In constrast, for kinesthetic haptic devices, added latency was not correlated with perceived stiffness at all and was negatively correlated with perceived damping [14], [15], [16], while reduced refresh rate was correlated with a decrease in perceived stiffness [17], [18], [19]. Our participants also showed an average decrease in their 95% confidence intervals of approximately 25% for both stiffness and damping tests from latency tests to refresh rate tests. This increased consistency of results for refresh rate tests suggests humans may be more comfortable with the effects of lower refresh rate than the effects of higher latency.

A. *Underestimation of Perceived Stiffness*

Perceived stiffness was underestimated by participants in both tests before latency or refresh rate was altered. Even when no latency was added during the latency study, perceived stiffness of the 150 N/m reference stiffness was only 125 N/m. And without reduction of refresh rate during the refresh rate study, perceived stiffness of the 150 N/m reference stiffness was 135 N/m. In both of these cases, the actual reference stiffness of the box was above the average participant perception of stiffness. Because no time effect of any sort had been added, these trials were controls and the perceived stiffness should ideally match the reference stiffness. We believe this discrepancy is due to the location of the virtual rectangles with respect to the participant. During the test, the location of the reference and tunable rectangles were maintained so that the reference rectangle was to the right and tunable rectangle was to the left. As a consequence, it is possible that all perceived stiffness values may have been slightly underestimated due to the extension effect from the body that decreases perceived stiffness [19]. However, since the entire experiment was conducted under the same conditions, this underestimation of stiffness should not affect the relationship we observed as a result of induced latency and refresh rate.

B. *Latency and Refresh Rate Relationship with Perceived Stiffness*

Latency and refresh rate were both positively correlated to perceived stiffness as time delay was added. Upon performing a simple linear regression, for latency the slope was 0.47 (N/m)/(ms) with an R-squared value of 0.22 while for update time the slope was 0.69 with an R-squared value of 0.47. Such large R-squared values are not surprising considering the variability in participant data, but it is also possible that the relationship between perceived stiffness and time delay is not linear. ANOVA results also suggested a nonlinear relationship, as statistically significant differences for both latency and refresh rate with perceived stiffness were found between most of the first three data points and the last three data points. Thus, it is possible that the relationship is a step function or similarly shaped power function. We propose that there exists a value of time delay (either latency and refresh rate) after which the perceived stiffness drastically increases. In the case of this experiment, this value is approximately 250 ms for latency and 50 ms for update rate (or 16.6 Hz when converted to refresh rate).

VII. CONCLUSIONS AND FUTURE WORK

This study examined the effects of time delays (latency and refresh rate), on force perception of stiffness and of viscous damping for force-controlled skin deformation feedback. To quantify these relationships, participants were asked to give their perceived force values when comparing two rectangles presented to them on a screen with varying material properties and time delays. By attempting to equalize the perceived stiffness and damping of the rectangles, the participants provided a metric to quantify perception of force.

These tests were performed using a custom force-controlled skin deformation device attached to a commercially available Omega.3 kinesthetic force-feedback device. The Omega.3 only provided position information within the haptic environment and forces were displayed only to compensate for gravity and thus isolate the effect of force-controlled skin deformation. The skin deformation device used an aperture to ground the subjects' fingers against the device to only render skin deformation in the tests.

The results from this study showed that latency and refresh rate have similar effects on perceived stiffness and perceived viscous damping. Participants were more consistent in their perception when doing refresh rate tests, indicating humans may be predisposed to changes in refresh rate than to changes in latency. For both latency and refresh rate, as the associated time delay was added, perceived stiffness increased significantly. This relationship does not seem to be linear and instead resembles a step function with a change at 250 ms for latency and 50 ms for refresh rate, after which the perceived stiffness drastically increased.

These results indicate that a force-controlled skin deformation feedback device has drastically different effects on perceived force compared to a traditional kinesthetic force-feedback haptic device. For both latency and refresh rate, as time delay increases, perceived stiffness does not change until it reaches approximately 250 ms for latency and 16.6 Hz for refresh rate, after which perceived stiffness increases significantly. Damping did not have any statistically significant changes with latency and refresh rate.

Further research should be done to confirm these trends and model the mathematical relationship between time delays and force perception with skin deformation feedback. Additionally, further comparison of displacement-based and force-controlled skin deformation feedback should be performed to determine their similarities and differences in terms of control accuracy and user perception. In addition, the combination of kinesthetic force feedback and force-controlled skin deformation should be examined. This combination could potentially create a more stable form of haptic feedback that can handle higher degrees of latency and lower refresh rates than current systems can endure, while maintaining a high degree of realism.

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