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Stiffness Discrimination with Visual and Proprioceptive Cues

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This study compares the Weber fraction for human perception of stiffness among three conditions: vision, proprioceptive motion feedback, and their combination. To make comparisons between these feedback conditions, a novel haptic device was designed that senses the spring behavior through encoder and force measurements, and implements a controller to render *linear* virtual springs so that the stimuli displayed haptically could be compared with their visual counterparts. The custom-designed, torque-controlled haptic interface non-invasively controls the availability of proprioceptive motion feedback in unimpaired individuals using a virtual environment. When proprioception is available, the user feels an MCP joint rotation that is proportional to his or her finger force. When proprioception is not available, the actual finger is not allowed to move, but a virtual finger displayed graphically moves in proportion to the user's applied force. Visual feedback is provided and removed by turning on and off this graphical display. Weber fractions were generated from an experiment in which users examined pairs of springs and attempted to identify the spring with higher stiffness. To account for slight trial-to-trial variations in the relationship between force and position in the proprioceptive feedback conditions, our analysis uses measurements of the actual rendered stiffness, rather than the commanded stiffness. Results for 10 users give average Weber fractions of 0.056 for vision, 0.036 for proprioception, and 0.039 for their combination, indicating that proprioception is important for stiffness perception for this experimental setup. The long-term goal of this research is to motivate and develop methods for proprioception feedback to wearers of dexterous upper-limb prostheses.

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Stiffness Discrimination with Visual and Proprioceptive Cues

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ABSTRACT

This study compares the Weber fraction for human perception of stiffness among three conditions: vision, proprioceptive motion feedback, and their combination. To make comparisons between these feedback conditions, a novel haptic device was designed that senses the spring behavior through encoder and force measurements, and implements a controller to render *linear* virtual springs so that the stimuli displayed haptically could be compared with their visual counterparts. The custom-designed, torque-controlled haptic interface non-invasively controls the availability of proprioceptive motion feedback in unimpaired individuals using a virtual environment. When proprioception is available, the user feels an MCP joint rotation that is proportional to his or her finger force. When proprioception is not available, the actual finger is not allowed to move, but a virtual finger displayed graphically moves in proportion to the user's applied force. Visual feedback is provided and removed by turning on and off this graphical display. Weber fractions were generated from an experiment in which users examined pairs of springs and attempted to identify the spring with higher stiffness. To account for slight trial-to-trial variations in the relationship between force and position in the proprioceptive feedback conditions, our analysis uses measurements of the actual rendered stiffness, rather than the commanded stiffness. Results for 10 users give average Weber fractions of 0.056 for vision, 0.036 for proprioception, and 0.039 for their combination, indicating that proprioception is important for stiffness perception for this experimental setup. The long-term goal of this research is to motivate and develop methods for proprioception feedback to wearers of dexterous upper-limb prostheses.

Index Terms: H.5.1 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O; H.1.2 [Models and Principles]: User/Machine Systems—Human factors; J.4 [Social and Behavioral Sciences]: Psychology

1 INTRODUCTION

A poorly understood aspect of the human experience is the appreciation of where and how our body parts move in space. This sense is known as proprioception and is often referred to as the "sixth" sense. The ease with which unimpaired humans accomplish activities of daily living is a reminder of the precise control that we have over our limbs and joints, and it stands in stark contrast to the character of movements made by current commercially available prosthetic limbs.

Ongoing prosthetics development projects seek to create artificial limbs that emulate human sensory and motor capabilities. A variety of tactile and force sensors are included in these new limbs, and new interface techniques, such as targeted reinnervation [11], promise to improve limb control by feeding back outputs from these sensors to the wearer. However, without the proper integration of proprioception, we hypothesize that the movements of these devices will be jerky, individuated, and robotic. Proprioception also provides the context in which tactile sensations are interpreted; one must know the configuration of one's fingers to easily interpret the tactile cues from a grasped object. It seems clear that wearers of prosthetic limbs need a rich set of sensory signals to enable graceful motion and natural interaction with the physical world.

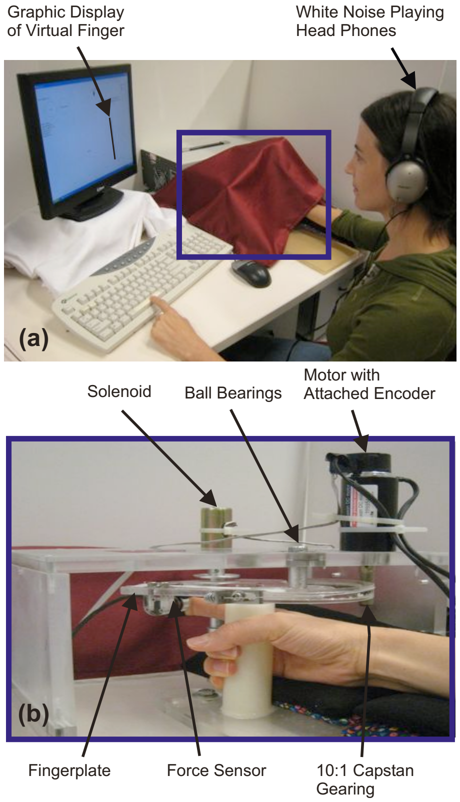

Figure 1: (a) Setup for stiffness discrimination experiments and (b) custom torque-controlled haptic interface for the right index finger.

Despite its obvious importance, much about proprioception is unknown. From a neurophysiology perspective, we do not completely understand how it is coded in the afferent discharge nor where or how it is processed in cortex. Little research has examined how it is used in movement control and perception of the environment. Prior work on the role of motion proprioception in movement control [8, 10] demonstrated that proprioception improves success rate during targeting tasks both in the presence and absence of vision, but much remains to be explored on this topic.

In this paper, we seek to determine whether proprioceptive feedback has a significant impact on the human ability to perceive the stiffness of an environment. We chose to examine stiffness because it is a fundamental mechanical property that can be used to distinguish objects from one another [16], and because it provides information about how an object should be manipulated. Stiffness depends on a relationship between force and position, so proprioception is clearly relevant.

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A unique aspect of this study is that we seek to compare performance between matched proprioceptive motion feedback and visual feedback cases. Rather than reporting an open-loop commanded stiffness, we built and controlled a haptic device that could sense the behavior of the haptically rendered virtual springs (Figure 1). Below we provide evidence that our device and controller do render linear springs. Using this knowledge, we make comparisons of user performance in the presence and absence of visual and proprioceptive motion feedback.

2 BACKGROUND

Numerous studies have characterized various aspects of both human proprioception and stiffness discrimination. This section provides a brief review of prior work in these areas.

2.1 Proprioception

Proprioception is derived from a combination of afferent channels, including muscle spindle fibers, Golgi tendon organs, joint angle receptors, and cutaneous mechanoreceptors (stimulated by skin stretch) [17, 2, 5, 3]. Gandevia et al. also showed that an efferent signal also creates a perception of arm motion even when the actual arm is held stationary [6].

Prior studies have investigated the effects of proprioception on human performance using methods such as anesthesia [17] and ischemia [9] to 'remove' proprioception; in addition to the difficulties encountered in running an invasive experiment, these methods block tactile sensations making it difficult to decipher whether the absence of proprioception or tactile cues causes the observed outcomes. Muscle vibration is another means used to study proprioception; this method is noninvasive, however it alters the sensation, rather than blocking it [13]. Our interface allows for noninvasive testing of user performance in the presence and absence of proprioceptive motion feedback.

Our test bed can also be used to quantify the effect of artificial proprioceptive feedback. Others have already considered artificial feedback of proprioception for application to prosthetics, however none have compared performance using artificial proprioception to using natural proprioception and/or vision. Dhillon and Horch [4] discuss preliminary results in replicating the sensation of limb movement through connections to the peripheral nervous system. They showed that stimulation of amputee nerve stumps with intrafascicular electrodes could be used to provide feedback information about both grip strength and limb position. Bark et al. [1] developed a device for stretching the skin of the arm, and they found that skin stretch was a more effective modality than vibration in providing artificial proprioceptive feedback.

2.2 Stiffness Discrimination

Stiffness is the resistance of an elastic body to deformation by an applied force; compliance is its inverse. Stiff objects can be categorized by two types: (1) deformable surfaces (e.g., sponge) and (2) rigid surfaces (e.g., piano key) [12]. Here we investigate stiffness discrimination abilities for springs with rigid surfaces in the presence and absence of proprioceptive motion and visual feedback.

Numerous studies quantify human stiffness discrimination abilities, using a variety of experimental methods [15, 12, 19, 20, 21, 22, 23]. These studies obtained Weber fractions (WF) ranging from 0.15 to 0.99. In Section 5.2 we use the WF as a measure of one's ability to discriminate between springs.

Studies have also investigated the mechanisms humans use to perceive stiffness. Roland and Ladegaard-Pedersen [19] found that after anesthetizing either only the skin or both the skin and joints, muscle receptors and tendons provided sufficient information to discriminate springs. Srinivasan et al. showed that for deformable surfaces, tactile information alone is sufficient and proprioceptive information alone is insufficient for discrimination, whereas for rigid surfaces both tactile and proprioceptive feedback are necessary [20]. Investigating high level perception of stiffness, Tan et al. [21] looked into the effects of work and terminal force cues on compliance discrimination and identified that discrimination is possible even in the absence of work cues (or no proprioceptive motion feedback). Pressman et al. [18] presented eight models describing how humans identify stiffness. Their findings indicate that human perception of stiffness can be characterized by a least squares calculation of stiffness during the pushing phase.

LaMotte conducted a psychophysics study using real objects to understand the effect of factors including exploration tool, exploration type, and speed on discrimination abilities [12]. LaMotte found that humans are able to discriminate softness just as well using a stylus as using the fingerpad, that discrimination is better when tapping than when pressing, and that velocity affects discrimination in passive tapping but not active. These results were all used in designing our study.

Several groups have examined the roles of proprioception and/or vision in stiffness discrimination. Lecuyer et al. [15] found that a passive isometric input device (no proprioceptive motion feedback), used together with visual feedback, can provide an operator with a perception of virtual environment stiffness. The proprioceptive sense of the subjects was significantly "blurred" by visual feedback, giving them the illusion of using a non-isometric device. In [14], Lecuyer et al. found that some subjects are haptically oriented while others are visually oriented in resolving conflicts between haptics and vision. However, the majority of the subjects used both haptics and vision, and in these cases it was noted that visual information dominated. Varadharajan et al. [24] used a magnetic levitation haptic device and graphical depiction of a helical spring to demonstrate that the presence of vision enables better discrimination between different spring stiffnesses.

One marked feature of the literature to date in stiffness discrimination is that there is little validation that the stiffness displayed by a haptic device is actually the desired stiffness. The present study is the first to compare carefully controlled haptic stiffness stimuli with their visually portrayed analogs.

3 APPARATUS

We built a novel custom impedance-type haptic device to record both the subject's finger position (via an encoder) and their applied finger force (via a force sensor) with the goal of rendering linear virtual springs and observing the exact behavior of the spring. This system also enables removal of the proprioceptive motion sense. Proprioception combines position, force, and skin stretch cues in order to determine where a limb is located in space and how it is moving. In this setup, we either allow the subject to move his or her finger or we mechanically lock the haptic device so that the finger cannot move. When the device is locked, the position and skin stretch cues are lost but the force cues remain. Thus, in both proprioception cases (*on* and *off*) the subject perceives the amount of force he or she is applying, and this force is related to the distance that a virtual finger travels. However, the subject feels his or her finger moving only when proprioceptive feedback is *on*.

The apparatus and testing method are also unique in that they remove sensations in a manner that is analogous to upper-limb prosthesis use. During large arm motions with a prosthesis, proprioceptive motion feedback is not readily available, yet forces proportional to the arm motions can be detected through the socket (where the prosthesis is attached to the residual limb). Likewise, with our device proprioceptive motion feedback is not available, yet force feedback remains.

3.1 Hardware

We created the one-degree-of-freedom impedance-type device shown in Figure 1. Initially, we attempted to render a virtual spring

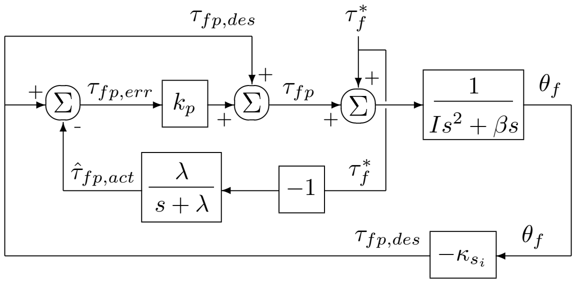

Figure 2: Controller block diagram. The torque applied about the finger plate (τ_{fp}) to resist motion of the right index finger is computed from actual measurements of the finger's angular position (θ_f) and applied finger torque (τ_f^*).

on a previously used admittance-type system [10], but the dynamics of that device prevented us from obtaining a linearly behaving spring, hence the creation of this new haptic device. It permits rotation of the right index finger about the metacarpophalangeal (MCP) joint, and it has a mechanical workspace spanning from approximately $-10°$ to $60°$ of rotation. The base of the apparatus is securely mounted to the table; the user rests his or her right arm on cushions and, to minimize extraneous movement, places the right hand around a cylindrical tube of outside diameter 3.2 cm.

The device uses a non-geared, backdriveable Maxon RE 40 DC motor with attached HEDS 5540 encoder. To this motor, we have attached a finger plate via a capstan drive with ratio of 10:1; this cable drive is used to minimize the effects of friction and backlash in the system and increase the system's torque output. The position resolution of the finger plate measurement is 0.018°, and the maximum continuous torque the system can apply is 1.8 Nm.

A solenoid is also affixed to the structure and is located at a distance of 0.125 m from the axis of rotation of the finger plate. This solenoid can mechanically lock the finger plate in place.

An ATI Nano-17 six-axis force/torque (f/t) sensor, with resolution of 0.0017 N along the z-axis, is affixed to the finger plate at an adjustable distance of ($l_f - 0.015$ m) from the MCP joint, where l_f is the length of the right index finger from the MCP joint to its tip. A velcro strap attaches the finger to the f/t sensor.

3.2 Feedback Conditions

3.2.1 Proprioception

Our system can operate under two conditions: the finger plate rotates (proprioceptive motion feedback is *on*) or the finger plate is locked in place (proprioceptive motion feedback is *off*).

For conditions when proprioception is *on*, the control law uses a bilateral proportional constraint and a low level torque controller. The controller block diagram of the system is presented in Figure 2. Both the torque applied by the user's finger, τ_f^*, and the finger's angular position, θ_f, are measured and updated at 1 kHz. The desired torque output to the force plate, $\tau_{fp,des}$, is related to this angular position by the spring stiffness constant, κ_{s_i}, as

$$\tau_{fp,des} = -\kappa_{s_i}\theta_f. \tag{1}$$

A low-level proportional torque controller makes the actual torque track the desired torque. The actual torque the finger applies, τ_f^*, is estimated from the f/t sensor and filtered by a low-pass filter with cutoff frequency of 150 Hz, resulting in $\hat{\tau}_{fp,act}$. A proportional torque error signal, $\tau_{fp,err}$, is then determined from

$$\tau_{fp,err} = \tau_{fp,des} - \hat{\tau}_{fp,act}. \tag{2}$$

The total amount of torque applied to the finger plate, τ_{fp}, is then a summation of the desired torque output to the finger plate and of the proportional torque error signal.

$$\tau_{fp} = \tau_{fp,des} + k_p\tau_{fp,err}, \tag{3}$$

where $k_p = 5.0$ is the proportional error gain. The proportional gain was chosen empirically to create stable, virtual springs across a variety of users.

If proprioceptive motion feedback is *off*, the solenoid mechanically locks the finger plate at zero degrees. Thus, when the user applies a force, the finger plate does not actually move.

3.2.2 Vision

For the conditions with visual feedback, a virtual finger is displayed on the computer screen to relay finger position to the user. The image of the virtual finger is a solid black line 0.195 cm wide and of length equal to that of the user's finger length (Figure 1). The line rotates about its lower endpoint by θ_{vf} (as defined below), counter clockwise from the zero degree vertical position. The visual display is updated at a rate of 33 Hz.

When vision is *on*, the angular rotation of the virtual finger, θ_{vf}, is dependent on whether proprioceptive feedback is provided. When proprioceptive feedback is *on*, the angular position, θ_{vf}, is set equal to the finger angular position, θ_f, as measured by the encoder. When proprioception is *off*, or the finger plate is mechanically locked at the zero degree position, θ_{vf} is calculated according to

$$\theta_{vf} = \frac{\hat{\tau}_{fp,act}}{\kappa_{s_i}}. \tag{4}$$

If visual feedback is *off*, no graphical representation is provided.

3.3 Ideality of Virtual Springs

In this study, we aimed to create linear virtual springs. Our haptic device measures both the user's angular finger position, θ_{vf}, and applied finger torque, τ_f^*, which allowed us to verify that the springs the subjects interacted with were very close to those we were commanding. Several other stiffness discrimination studies performed using haptic devices have been reported in the literature, but none show the behavior of the virtual springs used during testing. Without closed-loop torque control, dynamic effects such as inertia and damping alter the rendered impedance.

We commanded seven virtual springs, $\kappa_{s_1}, \cdots, \kappa_{s_7}$, enabling seven different stiffness values. Converting from the units of Nm/degree to N/m at the fingertip, these desired spring stiffness values are respectively $\kappa_{s_{1,\ldots,7}}$ = 245, 260, 275, 290, 305, 320, and 335 N/m, with $k_{s_4} = 290$ N/m being the standard stiffness.

Figure 3 demonstrates the linearity of the springs. This figure plots data from 25 trials for each of the six comparison springs and 150 trials for the standard spring. A study by Pressman et al. [18] suggested that humans detect stiffness during only the pushing portion of a spring manipulation. Thus, in this figure and in our data analysis, we use only the portion of data in which the subject was pushing on the spring.

4 EXPERIMENTAL METHODS

This experiment investigates the ability of humans to discriminate between virtual springs of different stiffnesses during active pressing with the index finger. We use the Method of Constant Stimuli [7] to determine the Weber fraction (WF) in stiffness discrimination under various feedback conditions. Two sensory feedback conditions are tested: vision (*on/off*), in which the subject can see a representation of his or her finger's location and motions, and proprioception (*on/off*), in which the subject's finger moves. There are four possible conditions; we investigate only the three cases in which at least one of the two feedback modalities is *on*, since the no feedback case does not provide the subject with any information from which to judge stiffness.

4.1 Task

The chosen task was to compare two different virtual springs and decide which one was stiffer. Each subject consecutively encountered two virtual springs of prescribed stiffness values and

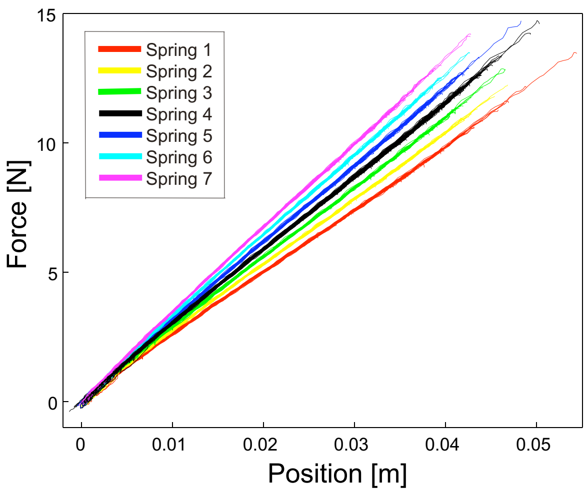

Figure 3: Finger position versus applied finger force for Subject 5. These data were acquired when only proprioceptive motion feedback was provided. For each spring press shown, the method of least squares was used to calculate a best fit line to the data, and the slope of this best fit line was defined as the estimated spring stiffness. The mean R^2 value for all fits is 0.98 with standard deviation of 0.01.

interacted with each one by pressing on the acrylic plate with the right index finger, resulting in a rotation of the finger about the MCP joint.

While interacting with the virtual springs, the subject was required to maintain contact with the apparatus through use of a velcro strap. We imposed this restriction because a prior study showed discrimination to be better when tapping than when pressing [12]. Additionally, the subject was asked to rotate the finger at a speed less than 100 deg/sec, since the virtual spring stiffness changed slightly depending on the user's exploration speed. LaMotte has shown that this speed limitation does not affect one's ability to discriminate between springs [12]. During practice trials only, a visual marker indicated the subject's finger speed as well as the minimum and maximum speed. Additionally, during both practice and experimental sets, a visual indicator appeared on the screen instructing the subject to slow down if he or she exceeded the threshold speed. To ensure comprehension, the subject had to press the space bar to remove this visual indicator.

For each trial, subjects were presented with two springs: a standard spring (κ_{s_4}) and a comparison spring ($\kappa_{s_{1,\cdots,3,5,\cdots,7}}$). The order in which these springs were presented was randomized. The subject was permitted to explore each spring for an unlimited amount of time, and a graphical display indicated which spring was being explored. In order to switch springs, the subject was instructed to apply less than a threshold force with the right index finger and to press the space bar on the keyboard with the left hand. If the subject had not returned to the zero degree position before attempting to switch between springs, an error message was displayed and the subject was asked to return his or her finger to the zero position and to hit the space bar once again. The subject could switch between virtual springs as many times as desired. When a decision was made as to which spring was stiffer, the subject pressed the '1' or '2' key on the keyboard with the left hand, corresponding to Spring 1 and Spring 2, respectively. This marked the completion of a trial, and the same process was repeated for all trials.

4.2 Experimental Procedures

The experiment was performed in two sessions lasting approximately two hours each. The sessions were held on two consecutive days to minimize fatigue and boredom. To begin, the subject was introduced to the experiment and signed a consent form. The length of the subject's right index finger, l_f, was measured as the distance from the MCP joint to the finger tip. Then the subject was seated comfortably next to the experimental setup. The investigator adjusted the apparatus and seat height so that the right index finger and hand were situated at the appropriate location on the haptic device. The subject was instructed to grasp the cylindrical tube.

After reviewing instructions, the subject completed a practice session of three sets of six trials each of the stiffness discrimination task. Each set consisted of trials with only one of the following three conditions: (1) Vision Only, (2) Proprioception Only, and (3) Vision and Proprioception. Each of the six trials corresponded to one of the six comparison stiffness values. The subject was allowed to repeat this practice session as many times as desired until he or she felt comfortable with the experiment and set up. After the practice session, the experimental trials began.

During the experimental sets, the apparatus and the subject's hand were hidden from view by a thin curtain. Additionally, the subject wore headphones playing white noise to prevent distractions from noise in the room or the apparatus.

Each of the six comparison stiffness values was paired with the standard stiffness value 25 times for a total of 150 trials for each of the three sets of feedback conditions. The placement of the standard spring (Spring 1 versus Spring 2) was randomly determined for each trial. Additionally, the order of the comparison springs and the feedback conditions presented was randomly determined for each subject. To avoid fatigue, after every 25 trials subjects were forced to take a break spanning a minimum of one minute and a recommended maximum of five minutes. Following each trial, the corresponding data that had been stored at 100 Hz were saved to a file. At the end of each set, the subject was asked to note the difficulty of discriminating between the springs with the feedback conditions available by using the mouse to select one of the squares on the screen stating 'very easy', 'easy', 'moderate', 'difficult', or 'very difficult'.

Upon completion of all three sets, the subject completed a questionnaire. In addition to providing information such as age and gender, the subjects ranked their opinions on the importance of the provided feedback conditions in successfully discriminating stiffnesses. A '1' was assigned to the feedback type that was most useful to the subject in completing the task, and a '3' to the least useful feedback type. The subjects provided an explanation of their ranking order. Last, the subjects commented on the methods they used when discriminating between the springs for each of the feedback conditions.

4.3 Subjects

Approval from the Homewood Institutional Review Board was obtained to collect data from human participants in this study. Subjects included 3 male and 7 female subjects in the age range 18 to 34. The subjects' right index finger length ranged from 8.0 to 10.0 cm. Subjects' self-reported experience with virtual environments spanned very little to expert. All subjects were healthy and reported no neurological illnesses or right hand impairments. In order to motivate subjects to participate in and complete the experiment, monetary compensation was provided. Subjects were paid a predetermined specified amount for completion of the experiment, and an hourly rate up to this completion amount if they chose to end the experiment prematurely.

5 RESULTS

Although we collected both quantitative and qualitative data, here we present only the preliminary quantitative results. Specifically we look at the behavior of the virtual springs as well as the Weber fractions obtained for each feedback condition.

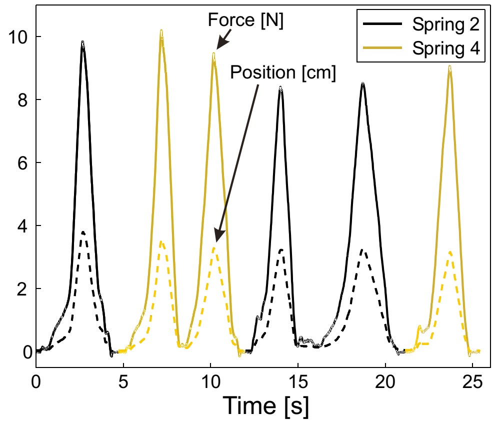

Figure 4: Position and force trajectories for a trial of Subject 5. These data were acquired when only proprioceptive motion feedback was provided.

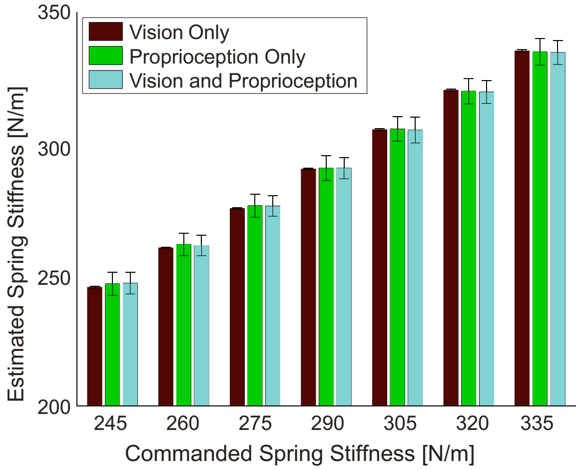

Figure 5: Estimated mean and standard deviation of stiffness values for each of the feedback conditions across all subjects.

5.1 Virtual Springs

During each trial, subjects were permitted to explore the two rendered virtual springs as many times as desired. For example, Figure 4 displays the finger position and applied finger force trajectories for one trial of Subject 5 while exploring springs 2 and 4 during the Proprioception Only set. The subject pressed the springs a total of six times and switched between the springs three times. The force and position data for Subject 5 during the entire Proprioception Only set is shown in Figure 3.

For each press of the spring, we estimated the stiffness of the rendered virtual spring. First we identified when a press was made and which spring, κ_{s_i}, corresponded to the press. Then we used the method of least squares to calculate the best fit line to these data. We call the slope of the best fit line the estimated stiffness value of the virtual spring.

Converting the user's angular finger position, θ_f, and applied finger torque, τ_f^*, from units of Nm/degree to N/m, we were able to identify whether we really achieved the stiffness of the seven commanded virtual springs, $\kappa_{s_1}, \cdots, \kappa_{s_7}$. Figure 5 summarizes the estimated spring stiffness results for all ten subjects under each of the three feedback conditions.

	Weber fractions		
	V Only	P Only	V and P
Subject 1	0.071	0.043	**0.037**
Subject 2	0.135	**0.048**	0.072
Subject 3	**0.036**	0.058	0.054
Subject 4	0.051	**0.028**	0.047
Subject 5	0.069	0.037†	**0.032**
Subject 6	**0.019**	0.025	0.023
Subject 7	0.025	**0.007**†	0.008
Subject 8	0.064	**0.029**	0.056
Subject 9	0.079	0.042	**0.037**
Subject 10	**0.010**	0.018	0.022
Mean	0.056	**0.036**	0.039

Table 1: Weber fraction results obtained in the Vision Only, Proprioception Only, and Vision and Proprioception sets using methods described in Section 5.2. † signifies that confidence was not found in the goodness-of-fit of the psychometric curve to the data. The Mean WF is the mean of the WFs listed for each subject, excluding WFs derived from psychometric functions lacking confidence. The minimum WF in each row is in boldface.

5.2 Stiffness Discrimination Results

In this study, we calculate the Weber fraction (WF) of stiffness discrimination under three feedback conditions–Vision Only, Proprioception Only, and Vision and Proprioception–by using the Method of Constant Stimuli, as described by Gescheider [7]. The WF was obtained by averaging the estimated stiffness values and the percentage of stiffer responses and fitting a psychometric curve to the data. The psychometric curve fit was made using **psignifit** version 2.5.6 (http://bootstrap-software.org/psignifit/), a software package that implements the maximum-likelihood method described by Wichmann and Hill [25]. From each psychometric curve fit, we obtained the point of subjective equality (PSE), corresponding to the stiffness value at which the percentage of stiffer responses is 50%. Ideally the PSE is 290 N/m: for our feedback conditions of Vision Only, Proprioception Only, and Vision and Proprioception we obtained PSE values of 287.8 N/m, 291.1 N/m, and 290.6 N/m, respectively.

Further, we found the lower and upper just noticeable differences (JNDs) by determining the stiffness values for which the percentage of stiffer response is 25% ($\kappa^*_{25\%}$) and 75% ($\kappa^*_{75\%}$), respectively. Thus,

$$JND_{lower} = PSE - \kappa^*_{25\%} \tag{5}$$

$$JND_{upper} = \kappa^*_{75\%} - PSE. \tag{6}$$

The JND was computed by averaging the lower and upper JNDs, and the Weber fraction (WF) was calculated by dividing this JND by the PSE:

$$JND = \frac{JND_{lower} + JND_{upper}}{2} \tag{7}$$

$$WF = \frac{JND}{PSE}. \tag{8}$$

The Weber fraction results obtained for all subjects under each of the three sensory feedback conditions are listed in Table 1.

6 DISCUSSION

The objective of this study was to quantify the importance of proprioception in a stiffness discrimination task, with the larger goal of understanding the need for proprioceptive feedback when using an upper-limb prosthesis. To accomplish this, we designed an experimental setup to render visual and haptic springs that are comparable. This paper presents our preliminary quantitative results. Additionally, a short video is available summarizing this work.

The rendering of linear virtual springs was crucial and unique to our experiment design, allowing comparison between the visual and haptic modalities. The actual behavior of the springs was determined using measurements from position and force sensors. Figure 3 demonstrates that the springs did not overlap in position-force space; the individual springs are clearly distinguishable and have linear behavior.

As shown in Table 1, four subjects had superior stiffness discrimination ability with only proprioceptive motion feedback, three with only visual feedback, and three with their combination. This could be due to differences in sensory weighting for each participant (i.e., focusing more on proprioception or more on vision) or due to lack of spatial alignment between haptic and visual stimuli. Our findings are similar to that of Lecuyer et al. where it seems that some subjects are haptically oriented while others are visually oriented.

The WFs we obtained were much smaller than those found in the literature, which range from 0.13 to 0.99 for tasks such as pinching between the thumb and index finger and pressing with a rigid stylus [15, 12, 19, 20, 21, 22, 23]. We hypothesize that the improved discrimination ability using our apparatus may be a result of our cleanly rendered springs, from which the effects of friction and inertia have been removed. It is reasonable to surmise that the presence of these dynamics in other systems may confound users' abilities to identify spring stiffness and hence make the discrimination task more difficult. Additional hypotheses for why our WFs may be lower include the uniqueness of our particular task (rotation of right index finger about the MCP joint) and methods used to compute the WF (Method of Constant Stimuli and Wichmann and Hill psychometric curve fitting software).

We believe that our experimental system will be a particularly useful tool for prosthesis studies, since it allows able-bodied subjects to manipulate an analog to an ideally responsive and controllable prosthesis, such as those currently under development by several research groups. For large arm motions, the set up is analogous to prosthesis use since even though proprioception is not readily available, forces proportional to the arm motions can be detected through the socket (where the prosthesis is attached to the residual limb). However, for hand motions with no net external force, such as pinching one's fingers together, our setup is not analogous since both proprioceptive and force feedback are not provided to the user. We may expect to observe even worse performance in the vision only case if force feedback were absent.

In the future, we will present additional findings from this study, including user ratings of the conditions. We will also create a device that provides artificial proprioception through sensory substitution. We will use the experimental setup described within this paper to evaluate the effectiveness of our artificial proprioception display in comparison to natural proprioception in the presence and absence of vision. Our findings will help guide the development of new prosthetic limbs and the manner in which they are interfaced with the human.

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