The Effect of Force/Motion Coupling on Motor and Cognitive Performance

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Abstract

Haptic cues take on meaning as a function of the context in which they are experienced. In interaction with objects in the physical environment, the context always includes a mechanical contact, at which point force and motion variables can be identified, and across which power may flow. In interaction with objects in a virtual or remote environment, it is not necessary for the contact across which haptic responses are rendered to be the same as the contact at which exploratory actions are applied. In this paper, we ask whether force/motion coupling has a significant impact on manual performance or cognitive load. We conducted an experiment in which n=7 participants attempted, while acting through a teleoperator, to discriminate three objects by their stiffness under two conditions. In one condition physical force/motion coupling was present, in the other it was not. To assess cognitive load, we engaged participants in a simultaneous cognitive task that included a response time measure. Results indicated no difference in manual discrimination performance. After rejecting the datasets of three of our participants based on inconsistent strategy by condition, we observed a small, non-significant trend toward lower cognitive load in the condition with physical coupling. Establishing a robust trend will require additional participants. While results are preliminary, we offer our paradigm as an important direction for new inquiry into the distinctions and interrelationships between information and its presentation in various haptic interface applications. Our work is aimed in particular at developing haptic feedback for use in prosthetic applications.

1 Introduction

Haptic cues displayed to a user through a motorized device are invariably intended to carry information and ultimately intended to hold meaning for the user. Oftentimes, the goal of haptic display is to produce sensations that emulate those encountered during interaction with the physical environment. This is the case both when cues are computer-synthesized and refer to a virtual environment, and when cues derive from sensors located in a remote environment. How meaning is ascribed to the information haptic cues carry is a process that goes on in the brain, and it likely involves a relationship between the cues and prior experience with physical environments. Another factor involved in the process of ascribing meaning to haptic cues is the motor action taken by the user [5]. That is, haptic cues are often responses to excitations imposed on the environment by a user. Certainly this is the case in teleoperation or even in haptic exploration of the prototypical virtual wall. What emerges as information and carries meaning then is the relationship between the user's motor actions (efferents) and the consequent haptic sensations (afferents). For example, stiffness of a remote or virtual object is carried in the relationship between the motion generated by motor action and force felt through haptic sensations. The stiffness might be called an invariant of the environment insofar that the force/motion relationship stays constant while the particular exploratory motor actions and haptic feedback vary.

In synthesized or even in remote environments accessed through a teleoperator, the unique opportunity exists to deliver haptic feedback in manners not necessarily consistent with experience in the physical world. For example, the forces generated by exploring a virtual wall with the right hand might be displayed by a haptic device in contact with the left hand. Ostensibly, the same information is available to the user, though it is displayed in a manner inconsistent with physical user/environment interaction. While such a non-physical action/reaction setup might seem poorly motivated, we suggest that it models the manner in which haptic display is often employed.

If a haptic device is used to render forces to a contact on the body other than the contact through which the user imposes motions, then a very different feedback loop is closed between the user and virtual object. In coupling with physical objects, only one mechanical contact is necessary, and the imposed motion and response forces are co-located (or might both be measured) across that single contact.

In our lab, we have often been surprised by the many, sometimes hidden roles that force/motion coupling plays. Sometimes it is our focus and goal, at other times it appears as an insidious confound in a human-subject experiment. We have found it near impossible to divorce the meaning applied to information contained in a haptic signal from the signal's effect on the kinematics and kinetics of a motor task. One cannot display a force without invoking a response motion from the body! On the other hand, certain uses of haptic display do not generate significant force/motion coupling between the user's body and a virtual environment. Vibrotactile display, for example, though it may be generated in response to a user's actions, is often presented through a different contact on the body than that involved in generating the action. Also, the mechanical response to vibration display is usually small in magnitude. The manner in which information is encoded using vibrotactile display (i.e., through amplitude and/or frequency, or location on the body) generally decouples reaction from action. In this sense, vibrotactile display is similar to display to the distance senses, vision and audition, where feedback loops involving conjugate force and motion variables are not involved.

A particularly compelling application for haptic display is interface to prosthetic devices, especially upper-limb prosthetics. Recent advances in materials, sensors, actuators, and microprocessors have led to the development of multi-degree of freedom prosthetic devices. Giving an amputee control over the multiple degrees of freedom and access to sensory feedback from these devices, however, remains a significant challenge [3] [6]. Alternatives are needed to the constant visual monitoring that an amputee uses to substitute for the missing tactile and kinesthetic cues. Sensory feedback from electronic touch and force sensors located on a terminal device would likely improve fine control, especially in contact tasks and tasks involving discrimination of mechanical properties—where vision often breaks down [3] [9] [1] [7].

It seems that control over a prosthesis should rely on feedback that is referred to the body: proprioceptive and haptic feedback [8, 4] (Figure 1 (b)). Ideally, such feedback would be referenced to the phantom limb [2]. For certain tasks, the appropriate sensory feedback would certainly be non-visual. For example, maintaining an appropriate grip force (say, to lift an egg without cracking it) would be difficult using vision in the absence of haptic feedback.

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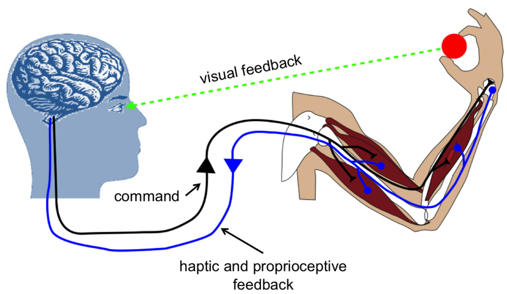
IEEE World Haptics Conference 2011
21-24 June, Istanbul, Turkey
978-1-4577-0298-3/11/$26.00 ©2011 IEEE

Such tasks rely on haptic feedback in able-bodied persons (Figure 1 (a)). In our present work, we aim to define and quantify what constitutes “appropriate” and “sufficient” haptic sensory feedback for a successful prosthesis interface. A particular measure in this context is the effect of force/motion coupling on the cognitive ability of an amputee to interpret referred haptic sensory information.

After achieving raw feasibility by selecting an actuator and sensor technology, common drivers for the design and implementation of haptic display technology are manufacturability, wearability, comfort, and cost. Unfortunately, the information carrying capacity or ability to provoke a given interpretation often takes second chair to technology decisions. What the user wants, however, is to find meaning in the incoming haptic cues, especially in the relationship between those cues and the motor actions that gave rise to them. Is the information carrying capacity of a given haptic cue related to its role in force/motion coupling? And also, if the action and display are decoupled, are relationships between afferents and efferents as readily apparent? In this paper, we begin to address these questions in the context of interface to prosthetic devices.



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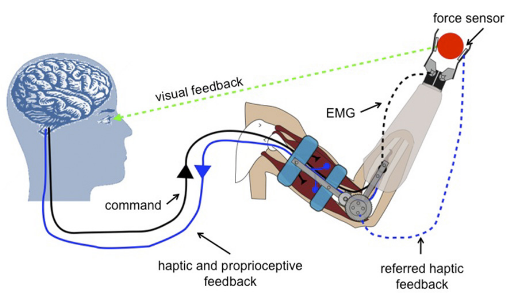


(b)

Figure 1: (a) Motor behavior of the able body is served by visual, proprioceptive (sensations pertaining to the relative position of various parts of the body) and haptic (sensations pertaining to movement and touch, especially interaction with the environment) feedback. (b) To establish sensory feedback of distal proprioceptive and haptic cues, we propose haptic display (e.g. force, vibrotactile feedback) to the proximal limb, referred from electronic sensors on the prosthesis.

1.1 Hypothesis:

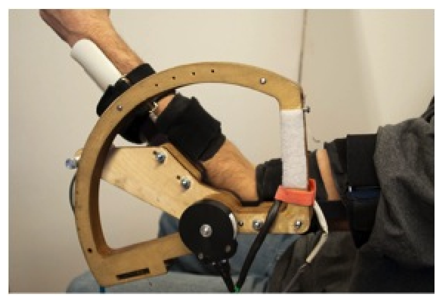
We expect that the brain interprets haptic information most readily when force/motion coupling exists at the contact through which the haptic information is presented. Such coupling is necessarily present in experience with the physical world. Removing this coupling requires a re-association in the brain that contradicts the expected meaning of a haptic cue based on prior experience with the physical environment. Forcing the brain to make this adjustment should have a deleterious impact the cognitive loading associated with the task.

2 Methods

2.1 Experimental Setup

The experimental setup comprises three major components: an elbow brace (exoskeleton) for the left arm that is motorized for torque feedback (Figure 2 (a)), a second, non-motorized exoskeleton for the right arm (Figure 2 (b)), and a motorized gripper (Figure 3). Both exoskeletons have a single axis of rotation that lines up with the elbow joint through the fitting of Velcro-tightened cuffs to the upper and lower arms. Position sensors are attached to both exoskeletons at the axis of rotation. A geared DC motor and capstan-drive transmission are incorporated into the motorized exoskeleton to create extension moments on the muscles spanning the left elbow. The mechanical advantage associated with the capstan drive is 17:1, yielding a maximum torque of 6 Nm. The motorized gripper is a linear DC motor with a strain gauge-based force sensor attached. The linear displacement of the gripper may be controlled in proportion to the angle of either exoskeleton. In operation, both exoskeleton/gripper configurations work as teleoperators with the exoskeleton as the master and the gripper as the slave. Grip forces sensed at the gripper are displayed as extension moments to the left elbow through the action of the motorized exoskeleton.

For the object identification task, three objects of distinct stiffness were used. The objects were leaf springs of varying beam length and cross section attached to wooden blocks. In the experiments the objects were named ‘soft’,‘medium’, and ‘hard’, referring to their stiffness relative to one another.



(a)

(b)

Figure 2: (a) The prototype motorized and instrumented exoskeleton spanning the elbow of an able-bodied participant. (b) The non-motorized exoskeleton spanning the elbow of an able-bodied participant.

2.2 Experimental Protocol

In the present study, n=7 able-bodied participants donned the motorized exoskeleton on the left arm, and the non-motorized exoskeleton on their right arm (see Figure 4). Each test consisted of 30 trials, where each trial alternated between the ipsilateral and contralateral conditions. In the ipsilateral condition, the motorized

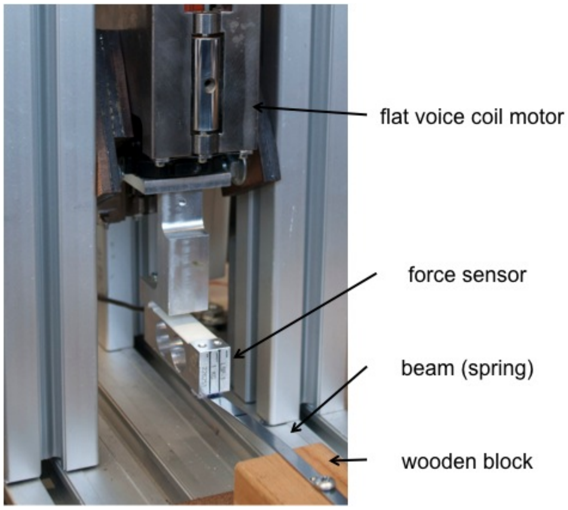


Figure 3: Motorized gripper with attached force sensor. A wooden block-mounted cantilevered beam 'object' is seen being pressed by the force sensor.

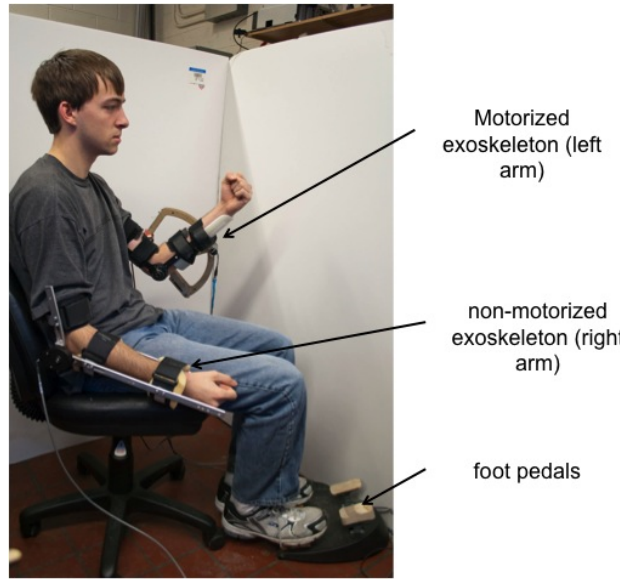


Figure 4: Participant wearing motorized exoskeleton on the left arm and non-motorized exoskeleton on the right arm. The participant is seated in front of the foot pedals used to respond to the auditory cues of the secondary cognitive task.

exoskeleton on the left arm was used to control the position of the motorized gripper, as well as display the force sensed by the gripper's force sensor (see Figure 5 (a)). In the contralateral condition, the non-motorized exoskeleton on the right arm was used to control the position of the motorized gripper, while the motorized exoskeleton on the left arm was used to display the force sensed by the gripper's force sensor (see Figure 5 (b)). During each trial, the participant was asked to complete a three alternative forced choice identification of the object within the gripper, while also completing a secondary task. The secondary task consisted of a reaction response to auditory cues. Tones of two different pitches (high and low) were generated in random order, and presented periodically throughout each trial. In response to each tone, the participant was instructed to press one of two foot pedals corresponding to the played tone. The tones played throughout the entirety of each trial at a rate of one tone (lasting 0.5 seconds) every one seconds. Each trial started when the tester announced "start" verbally and ended when the participant verbalized their object choice. Knowledge of results (KR) was provided at the end of each trial by the tester verbally providing the correct name ('soft','medium','hard') of the object just presented. In the ipsilateral condition the participant was instructed to only move their left arm. In the contralateral condition, the participant was instructed to move both arms together. In both conditions, the participant was allowed to explore and probe the object in whatever fashion they preferred, adhering to the previously mentioned constraints. Prior to testing, each particpant was trained in both the object identification task as well as the secondary task.

We measured the kinematics and kinetics of both exoskeletons, gripper, and foot pedals. In addition we recorded the tones generated during the secondary cognitive task, as well as object presentation and particpant choice in the object identification task. In order to test our hypothesis, we set as performance metrics the object identification accuracy (%), trial length, and cognitive task response times to cross a pedal threshold value. The threshold value was set at 20% of the total pedal excursion.

2.3 Assessments and data analysis

Our statistical analysis corresponded to 2 X 3 Condition (ipsilateral vs. contralateral) x Trial (3 blocks: 'soft', 'medium', 'hard') linear mixed model ANOVAs with block (10 trials each) as the repeated factor and particpant as a random factor. A p-value of 0.05 was used as the threshold to determine statistical significance.

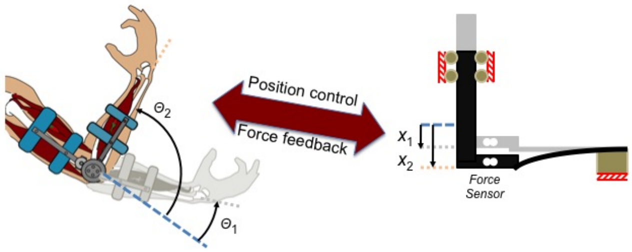
3 Results

The kinematic data (from the encoders on both exoskeletons and the encoder on the gripper), along with the kinetic data (the force reading on the gripper and the motor command on the motorized exoskeleton) contains information regarding what was experienced by the participants when each object was probed. The force/displacement traces recorded from the gripper for all ipsilateral trials (particpant 5) are shown in Figure 6 (a), and the force/displacement traces recorded from the motorized exoskeleton for all ipsilateral trials (particpant 5) are shown in Figure 6 (b). Similarly, force/displacement traces from the gripper and exoskeleton for all contralateral trials (particpant 5) are shown in Figure 6 (c) and (d), respectively. These traces have been colored (in postprocessing) by object and demonstrate that both the sensed stiffness (gripper) and referred stiffness (motorized exoskeleton) of each object fall into three distinct groupings. Differences between the kinematics or kinetics by condition (ipsilateral/contralateral) are not visually discernible in the graphs.

Across all three objects, there was no significant difference in the ability to accurately identify each object. Also, object identification success during the dual motor/cognitive task was not substantially different than performance during the training period that preceded the dual task. Figure 7 shows only nominal differences by object (hard, soft, medium) in identification accuracy under the ipsilateral and contralateral conditions.

Across the hard and medium objects there is no significant difference in the trial length (time duration between initiation by tester and verbal report of object identity by participant) between the ipsilateral and contralateral conditions. Figure 8 shows only nominal differences by object for the hard and medium objects but a substantial difference is evident for the soft object. Participants took on average only 3 seconds to report on the soft object in the contralateral condition and 5.5 seconds in the ipsilateral condition.

Figure 9 shows the response time on the cognitive task by condition (ipsilateral/contralateral) for each of our 7 particpants. The



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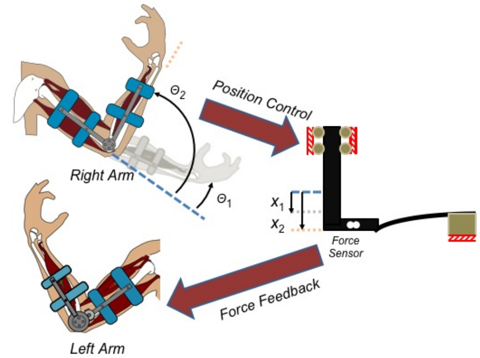
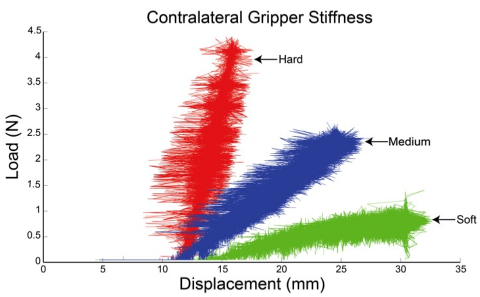


(b)

Figure 5: (a) Ipsilateral condition: left arm controls gripper position and left arm receives haptic force feedback. (b) Contralateral condition: right arm controls gripper position and left arm receives haptic force feedback.



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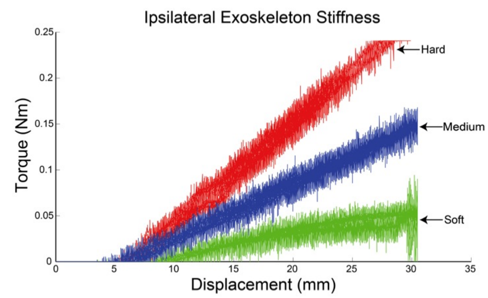

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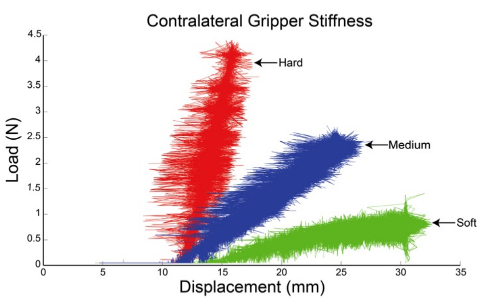

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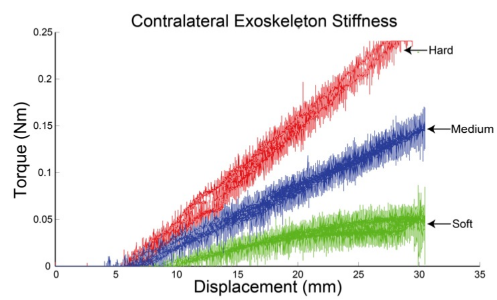

(d)

Figure 6: The force and displacement trajectories recorded at the gripper and exoskeleton are graphed against one another to assess whether information regarding distinct stiffnesses of the objects was present in the data. Subfigures (a) and (b) were recorded in the ipsilateral condition and (c) and (d) were recorded in the contralateral condition. Subfigures (a) and (c) pertain to the gripper and (b) and (d) pertain to the exoskeleton.

response time for a given trial is the average time (in milliseconds) between the onset of a tone and the crossing of a threshold in pedal excursion. Typical trials contained at least 4 tones and pedal responses. Response times were averaged across the right and left foot (high and low pitched tones) and incorrect responses were not rejected. Four of the 6 particpants have a shorter response in the ipsilateral condition. Particpants 4, 6, and 7 have a longer response time for the ipsilateral condition.

Across all particpants there do not appear to be significant differences by condition (ipsilateral/contralateral) ($p > 0.5$). However, inspection of the foot pedal responses of particpant 7 shows that many auditory cues lacked a response. That is, the means computed for particpant 7 included far fewer responses. Particpant 7 subordinated the cognitive task to a much greater degree than any of our other particpants. Also, particpant 7 had to be reminded several times during the experiment to continue responding to the cognitive task cues. Particpants 1 and 6 used a different strategy than the rest of our population sample. Instead of relying on forces felt in the left arm, they used the relative position of each arm as an indication of object. The hard object caused their arms to move out of sync the most, whereas the soft object barley affected the syncing (relative angle over time) of their left and right arms. On these two grounds, we decided to include the data only from particpants 2-5, all of whom used a strategy similar to one another.

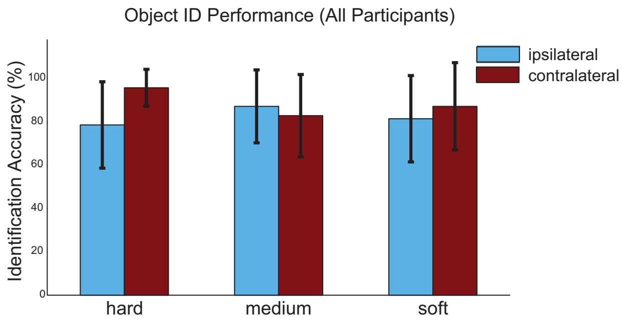

Figure 7: Accuracy in the verbal report of the identity of each object, by condition (ipsilateral, left blue bars and contralateral, right red bars). Error bars indicate 1 standard deviation of the mean across 20 trials for each object and condition, and across all participants.

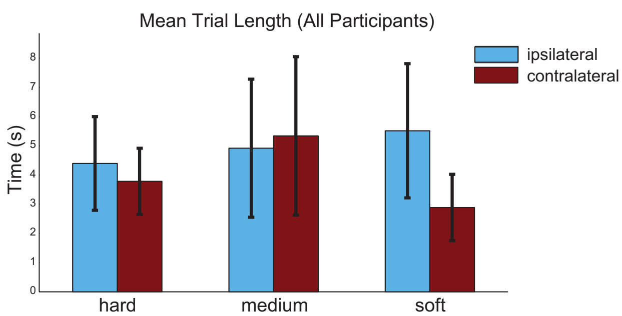

Figure 8: The duration of each trial by condition. Each trial is one object presentation. Error bars indicate one standard deviation of the mean across 20 trials for each object and condition and across all participants.

Including only particpants 2 through 5 (n=4) and considering particpant as a random effect and object (hard, medium, soft) and condition (ipsilateral/contralateral) as fixed effects, fitting a linear mixed model within subject comparion yielded a non-significant difference in response times (F=1.226, p=0.27), with the ipsilateral condition showing an advantage of 23 ms over the contralateral condition.

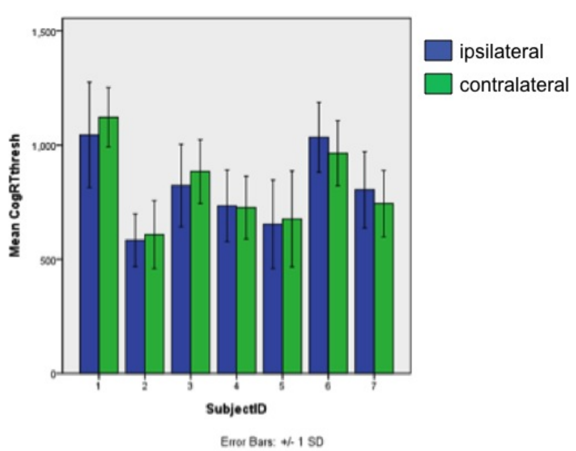

Figure 9: Cognitive Response Times for each subject by condition.

4 Discussion

In this study we were interested in determining whether it is necessary for the control and display associated with position command and force feedback to be coupled (co-located on the body) for effective performance in a manual task. While power-conjugate force and velocity variables can always be identified for a manual object-interaction task performed in a physical environment, the possibility exists for disassociation in interface to a virtual or remote environment. Especially for manual tasks requiring the perception of object properties that are invariants or relationships between force and motion, we hypothesized a difference in performance. The information is still available to determine object properties, but the perceptual processing in a task with disassociated force and motion must be different. We wondered whether differences might show in task performance or in indicators of cognitive load.

Thus we invited particpants to discriminate objects of varying stiffness in the standard, co-located condition, and in the mechatronic, disassociated condition. The standard condition involved both command and display about the left elbow and the disassociated condition involved command from the right elbow and display to the left. Results are somewhat weak in the present experimental dataset, though it appears that there exists a trend toward increased cognitive load in the disassociated condition. There did not appear to be any differences in task performance (accuracy in identifying the objects).

In pilot studies we noticed a distinct effect of the existence of motion in the left arm on the sensitivity to force display during the contralateral condition. How and when the particpant chose to move their left arm during a trial had an effect on the type of cues that were most apparent. Many particpants used these specific cues to distinguish object stiffness. In particular when the particpant held their left arm steady while moving their right arm, they used the force generated at that specified position instead of the entire stiffness spectrum they used in the ipsilateral condition. Also, the location at which they held their arm played a role. At smaller displacements, differentiation was difficult given that the differences in stiffness of each object were small. If the particpant allowed their left arm to move, force as well as position information became cues as to which object produced the greatest force and greatest rotation. In the end we settled on a protocol that required particpants to move both arms simultaneously, because it closely resembled the motion used in the ipsilateral condition. The increased torque caused by the stiffest object greatly reduced the range of motion of the left arm, as compared to the freely moving right arm. It is possible that this cue made the stiffest object easier to identify.

In future experiments we plan to make modifications to the cognitive task. The current cognitive task consists of a time response to discretely occurring events. Hence we are only assessing the cognitive load at periodic instances through each test. Therefore it is possible that if a particpant was capable of switching between tasks very rapidly, our current measurement method failed to capture the entire story. Using a continuous tracking task will provide a better measure of how the cognitive loading changes over time, and will prevent particpants from being able to switch attention between tasks without noticeable performance declines.

The determination of the role that force/motion coupling plays in the application of haptic technology has many benefits for the haptic community at large, and the specific application of haptics in prosthetics. Understanding how the presentation of haptic information has an effect on the brain's interpretion will lead to the development of haptic feedback systems that refer the interaction dynamics between a prosthetic device and environment back to the user in such a way as to facilitate the easiest interpretation and the highest function.

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