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Effects of Proprioceptive Motion Feedback on Sighted and Non-Sighted Control of a Virtual Hand Prosthesis

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Abstract

Current prosthetic devices lack the ability to provide proprioceptive feedback, requiring the user to visually track the device in order to accomplish the tasks of daily living. This work seeks to quantify the effect of proprioceptive feedback on the accuracy, speed, and ease of use of a one-degree-of-freedom virtual prosthetic finger in both sighted and unsighted conditions. An experimental apparatus was designed to allow a user to perform a virtual grasping task with and without visual and proprioceptive feedback. Preliminary results suggest that proprioception improves movement accuracy and ease of system use in the absence of vision.

Keywords

proprioception, vision, prosthetic limb control, motion control, human psychophysics

Disciplines

Engineering | Mechanical Engineering

Comments

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Effects of Proprioceptive Motion Feedback on Sighted and Non-Sighted Control of a Virtual Hand Prosthesis

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ABSTRACT

Current prosthetic devices lack the ability to provide proprioceptive feedback, requiring the user to visually track the device in order to accomplish the tasks of daily living. This work seeks to quantify the effect of proprioceptive feedback on the accuracy, speed, and ease of use of a one-degree-of-freedom virtual prosthetic finger in both sighted and unsighted conditions. An experimental apparatus was designed to allow a user to perform a virtual grasping task with and without visual and proprioceptive feedback. Preliminary results suggest that proprioception improves movement accuracy and ease of system use in the absence of vision.

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INDEX TERMS: H.1.2 [Models and Principles]: User/Machine Systems--Human information processing, H.5.2 [Information Interfaces and Presentation]: User Interfaces--Haptic I/O

1 INTRODUCTION

A survey of upper-limb prosthesis wearers in the United States revealed that one of their top research priorities is the ability to control the limb without watching it [1]. Current commercially available upper-limb prostheses provide little to no haptic feedback beyond socket forces, making non-visual control nearly impossible. Intuitively, one would expect proprioceptive feedback to be beneficial in everyday tasks that are done without visual feedback, such as putting on a hat or touch typing. We examine the effect of proprioceptive feedback on accuracy, speed, and ease of use of a virtual prosthesis in a simple motion control task, to quantify the advantages of incorporating proprioceptive feedback into new prosthesis development.

Much research has been done to determine the relative importance of visual and proprioceptive feedback in a variety of situations, including finger localization [2] and motion planning [3]. However, these studies generally involve either blocking the proprioceptive sense through anesthesia or indirectly determining the relative contributions of the senses by observing the results of conflicting feedback. Kuchenbecker et al. [4] took a new approach, where a user's force input controlled the motion of a virtual finger. Proprioceptive feedback was provided by allowing the index finger to move so it matched the movement of the virtual finger, or removed by holding the finger still. Their study showed that proprioceptive feedback improves accuracy and ease of use in both sighted and non-sighted conditions but results in slower movements. A probable reason for the slowing effect of proprioception is the study's inadvertent coupling of force input and proprioceptive feedback. In this work, we remove this effect by physically decoupling the force input from the proprioceptive feedback while still providing a natural mental coupling.

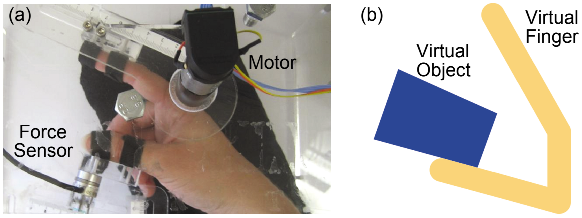

Figure 1. (a) Custom haptic device used in this study. Force input is obtained from the force sensor affixed to the thumb, and proprioceptive feedback is provided to the index finger when the motor allows the finger to move under an admittance control law. (b) The user is asked to move the virtual finger to grasp the virtual object. When visual feedback is provided, the virtual finger moves on the screen. Otherwise, it stays still.

2 EXPERIMENT DESIGN

As in [4], we consider a one-degree-of-freedom targeting task in which the movement occurs at the MCP joint of the right index finger. The user controls a virtual prosthetic hand to grasp virtual objects between the thumb and forefinger. Visual feedback is provided via a computer monitor, and a custom haptic device accepts force input and provides proprioceptive motion feedback.

Fig. 1(a) shows the haptic device used in this study. The user's right thumb is affixed to a force sensor through two Velcro loops. The right index finger is similarly affixed to an acrylic plate that is rotated by a motor positioned above the MCP joint. Thus, the thumb provides the input but remains stationary, and the index finger can be moved to match the position and velocity of the virtual finger. The system is mechanically adjustable to match the size of the user's hand, and pillows were provided to support the forearm to minimize arm movement. The force sensor, motor, and computer system were the same as those used in [4].

The motion of the virtual finger is controlled through an admittance relationship between torque and velocity, with a force dead band, F^- to F^+, implemented in software to account for varying resting force. The thumb torque τ_t is calculated from

$$\tau_t = \begin{cases} (F_t - F^-)l_t, & F < F^- \\ 0, & F^- \leq F_t \leq F^+ \\ (F_t - F^+)l_t, & F > F^+ \end{cases}$$

where F_t is the measured thumb force input and l_t is the measured

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thumb length. The virtual finger velocity ω_{vf} is proportional to the thumb torque, with an admittance of 500 $\frac{°/s}{N \cdot m}$ as the proportionality constant, chosen as a comfortable value for users based on pre-experiment testing. This control law was chosen to mimic the behavior of many commercially available myoelectric prostheses, which generate a velocity proportional to the myoelectric signal and contain a dead band, or sensitivity, set for the individual user to prevent undesired movement (e.g. [5]).

During an interaction, visual feedback can be provided by showing the virtual hand moving on the computer screen. The motor can provide proprioceptive feedback by allowing the user's real finger to move to match the movement of the virtual finger. To remove proprioceptive feedback, the real index finger is held stationary. The motor control law is described in [4]. Feedback is presented in four combinations: Visual + Proprioceptive (V+P), Visual + No Proprioceptive (V+NP), No Visual + Proprioceptive (NV+P), and No Visual + No Proprioceptive (NV+NP).

The task presented to the user is to quickly and accurately position the virtual finger tangent to the virtual object, stop the finger there, and press a computer key to indicate completion of the task. This task is analogous to lightly gripping an object. Subjects were aware that the finger's movement was controlled by the thumb, but they were asked to imagine pinching the object. Fig. 1(b) shows the virtual object and fingers as seen by the user. In each trial, the virtual finger begins 30° from the fully open position. Virtual objects appear in four different sizes to command target finger positions of 42°, 54°, 66°, and 78°. To enforce the stopping requirement, each trial is allowed to end only if the virtual finger velocity is zero when the stop key is pressed. Ten subjects have participated in the experiment.

The experiment progresses as follows. The system is adjusted to fit the subject's hand, and the force dead band is calibrated by measuring the forces applied when the user is relaxed. Then the user completes four identical practice sets of 12 trials each, one under each feedback combination in the order V+P, V+NP, NV+P, NV+NP. Between sets, subject rates the difficulty of each set. After the practice sets, experiment sets of 24 trials each are conducted in the same manner with targets and sets presented in random order.

3 PRELIMINARY RESULTS

Our preliminary analysis focuses on accuracy, ease of use, and speed. To obtain a measure of accuracy, unsigned position error at the end of each trial was recorded. Fig. 2(a) shows the mean unsigned position error for each feedback condition. The average ease of use ratings are reported in Fig. 2(b). The average speed for each trial was computed over the time that the virtual finger was moving, to remove time during which the finger was stationary at the start and end of a trial. The means and standard deviations of these average speeds are reported in Fig. 2(c) for each condition.

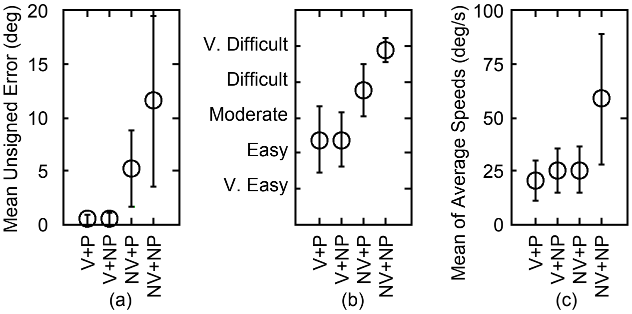

Figure 2. (a) Mean unsigned error for each feedback condition taken over all subjects and trials. (b) Mean difficulty rating for each condition taken over all subjects. (c) Mean of average speeds for each condition taken over all subjects and trials.

4 DISCUSSION

The preliminary data reported here have not been analyzed statistically, but the results suggest possible trends to be investigated as the study progresses.

Fig. 2(a) implies that visual feedback decreases position error whether proprioceptive feedback is present or not. In contrast, proprioceptive feedback appears to decrease position error only in the absence of visual feedback. When visual feedback is present, the addition of proprioceptive feedback seems to have no effect. Compared to the no-feedback case, adding visual feedback seems to decrease error more than adding proprioceptive feedback. Also, more variation in error is present without visual feedback. Not surprisingly, this suggests that vision is more precise than proprioception, likely due to the JND in joint angle being larger than the position change one can discern visually.

Similar trends can be seen in the ease of use ratings in Fig. 2(b). Both proprioception and vision make the system easier to use, and vision has more effect than proprioception. Again, proprioception appears to have no noticeable effect if vision is present.

In Fig. 2(c), both vision and proprioception seem to decrease average speed, regardless of whether the other is present. This result runs counter to what we might expect, that more feedback allows quicker, more accurate movement. However, a comparison of speed and accuracy reveals that higher average speeds are generally associated with larger position errors. This suggests that with more feedback, users were able to be more accurate but moved more slowly in order to take advantage of the extra information.

A comparison of these preliminary results to those reported in [4] shows that not all of the results are in agreement. While both agreed that proprioception improved accuracy and ease of use in non-sighted conditions, the current study found no improvement as a result of proprioception when vision is present. Also, while the previous study found an increase in speed with the addition of visual feedback, this study found a decrease in speed with the addition of proprioception or vision. It is hoped that further analysis will reveal explanations for these differences.

Preliminary results indicate that this study has successfully avoided the input/output coupling present in the previous experiment [4]. Further analysis is needed to quantify the effects of proprioception on motor control. However, the data thus far imply that proprioceptive feedback significantly improves accuracy and ease of use in motor control tasks when vision is not available, confirming that artificial proprioceptive feedback in a prosthesis would be beneficial to the wearer in everyday life.

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