Effects of Body-powered Prosthesis Prehensor Stiffness on Performance in an Object Stiffness Discrimination Task

Anton Filatov, Ozkan Celik, Member, IEEE

Abstract—In this paper, we present results from two human subject experiments focusing on effect of prehensor stiffness on object stiffness discrimination task performance in a body-powered prosthesis. Humans have the ability to alter the directional endpoint stiffness of their arms through co-contraction of agonist/antagonist muscle pairs. In the area of prosthesis design, while the need for position and force control has long been recognized, the concept of end effector stiffness modulation has been mostly ignored. In this study we attempt to broaden the existing knowledge base by (1) using an experimental setup which mimics the control inputs of a shoulder-driven body-powered prosthesis operated in voluntary closing (VC) mode, and (2) exploring the effect of end effector stiffness modulation on the quality of haptic feedback the user receives about the environment. Results of the first experiment indicated that tuning of prehensor stiffness in a body-powered prosthesis can increase the performance of the user in correctly and more easily identifying objects with varying stiffness.

I. INTRODUCTION

Humans have the ability to alter the directional endpoint stiffness of their arms through co-contraction of agonist/antagonist muscle pairs [1], [2], and do so to match the requirements of a particular task [3]–[5]. Although end point force generation can also contribute to limb stiffness [6], [7], humans can change the stiffness of their arms independently of net joint torque [3], [8]. This ability is useful when attempting to adjust to unstable environments [3], [4], [9] or performing a constrained task [10]. It should be noted that while stiffness is only a part of the overall end effector impedance, evidence for damping modulation by humans is less conclusive [7], [11].

In the area of prosthesis design, while the need for position and force control has long been recognized, the concept of end effector stiffness modulation has been mostly ignored. Current commercially available upper-extremity prosthetic devices make virtually no provisions for modulating the stiffness of the end effector. In the case of body-powered prostheses, the end effector stiffness is a function of the stiffness of the spring in the prehensor, and the stiffness of the body joint driving the actuator. However, the prehensor spring (and therefore stiffness) cannot be modified on the fly, and the body joint can control stiffness in only one direction, a function of the cabled actuation system. In EMG-controlled, robotic devices, joint stiffness is completely independent of user intention, and is secondary to velocity, and in some cases, force control.

Recently several groups have begun to focus on this issue [12]–[15]. Both Ajoudani et. al. [12], as well as Hocaoglu and Patoglu [14] demonstrated tele-impedance control of a robotic system as a stand in for a prosthetic device. Blank et. al. [15] demonstrated the utility of impedance modulation in two tasks (contact force minimization and trajectory tracking) using both virtual and robotic systems. However, these previous studies have been subject to several limitations. In general, they either used idealized modes of control [15], or were focused on EMG-driven systems, which while extremely promising, are less commonly used than the body powered prostheses [16]. Additionally, all of them focused on the role stiffness modulation plays in enabling either precise motion, or stability against external disturbance.

In this study we attempt to broaden the existing knowledge base by (1) using an experimental setup which mimics the control inputs of a shoulder-driven body-powered prosthesis operated in voluntary closing (VC) mode, and (2) exploring the effect of end effector stiffness modulation on the quality of haptic feedback the user receives about the environment.

The force feedback that a body powered prosthesis displays to a user during interaction with an object is proportional to the sum of $K_D$, the device (prehensor) stiffness and $K_O$, the object stiffness, i.e.

$$F \propto K_D + K_O$$

Thus, if

$$K_D > K_O$$

the majority of the feedback force, $F$, is dedicated to providing the user feedback about the internal workings of the gripper rather than to informing the user about the response of the object. We therefore hypothesize that a condition in which $K_D$ is minimized will result in optimal user performance in an object stiffness discrimination task.

This paper presents the results of two related experiments. Experiment 1 had two goals: (1) to test the hypothesis that prosthesis end effector stiffness impacts the ability of a user to distinguish between two objects of different stiffness, and (2) to examine whether this effect is present when manipulating real and virtual objects. The subjects were asked to use a prosthesis simulator (PS) system (shown in Fig. 1, see [17] for details on an earlier version of the device) to interact with an object and identify it as either a low or
Fig. 1. Prosthesis simulator experimental setup.

Fig. 2. Detail of prosthesis simulator end effector linkages.

a high stiffness spring. This task was performed with both a low and a high device stiffness, and with real and virtual objects. The second experiment was designed to explore the trends suggested by Experiment 1 further, by increasing the number of device stiffness settings from two to three, and raising the difficulty of the task by expanding the object set from two to four. Only virtual objects were used for Experiment 2.

II. METHODS

A. Experiment 1: Real and Virtual Objects

1) Setup: The subject was seated to the left of the PS device, which was held immobile in an adjustable vise on a table. The subject’s elbow was resting on a support and their right hand was holding the handle of the PS. The one degree of freedom end effector gripper was mechanically linked by a cable to a harness around the subject’s left shoulder, mimicking the actuation system of a body-powered upper limb prosthesis. Tension on the cable, provided by the movement of the subject’s left shoulder actuated the gripper, closing it. Interaction of the gripper with any object, real or virtual, resulted in an increase of the torque on the gripper shaft, which was displayed as a proportional increase in the force delivered through the mechanical linkage to the subject’s shoulder. It should be noted that while many body-powered prostheses operate in the voluntary opening mode, only voluntary closing devices, such as the one used in this study here, give the users direct sensory feedback about the environment. Such devices are usually utilized for demanding or delicate tasks.

The lever arm between the cable and the gripper shaft was 28.1 mm, and the gripper had a range of motion of 90°. A Maxon RE 30 DC (24V, 3.81A) motor was also mechanically linked to the gripper shaft, through a cable drive with a gear ratio of 12:1 (Note: all torque measurements and constants are reported at the gripper shaft). A picture of this arrangement is shown in Fig. 2. Through all experiments, this motor was used to simulate a linear torsional spring with a constant of $K_D$, acting to keep the gripper open, approximating the behavior of a voluntary closing prosthetic prehensor. For this experiment, the value of $K$ alternated between 41.4 mNm/° and 103 mNm/°, or $K_D^-$ and $K_D^+$ respectively, representing the lowest and highest practical stiffness settings for the device.

Two Slo-Foam™ hand exercise foam blocks with different spring constants were selected as experimental objects. Both were fitted with a custom interface to enable quick attachment and detachment to and from the gripper of the PS. In order to create virtual representations of these objects, their effective torsional spring constants, $K_O^-$ and $K_O^+$ for the softer and harder of the two sponges respectively, had to be experimentally determined. Repeated automated compression of the sponges with the PS gripper showed that $K_O^- \approx 120$ mNm/° and $K_O^+ \approx 360$ mNm/° (the nonlinear stiffness behavior was approximated by a linear model, see the Discussion section for a more detailed discussion of this aspect). During virtual object trials, these values were used to model the sponges as linear torsional springs, implemented by the gripper motor once the subject closed the gripper past the contact threshold. This threshold was also used to measure trial time for all cases. For real objects, the threshold was set to 20°, while for virtual objects the threshold was shifted further, to 30°. This change was made in an attempt to avoid saturation of the motor due to combined torques required to represent the device stiffness and the virtual spring. Thus, the total force, $F$, displayed to the subject during any individual trial was

$$F = l(rK_D + (r-t)K_O)$$

where $l$ is the lever arm of the harness, $K_D$ is the device stiffness, $r$ is the displacement of the gripper from its resting position in degrees, $t$ is the contact threshold, and

$$K_O = \begin{cases} K_O^- & \text{if } r \geq t \\ 0 & \text{if } r < t \end{cases}$$
During all experiments, a screen was placed between the subject and the PS, blocking their view of the gripper and eliminating the effects of visual feedback. A keyboard used for recording the subject’s responses was placed within reach of the subject’s left hand.

2) Procedure: All subjects participated in two separate data collection sessions, with each session comprised of two trial blocks dedicated to a particular object type—real or virtual. For the duration of a trial block the device stiffness, $K_D$, was set to either $K_D^+$ or $K_D^-$. In order to minimize learning effects, the order of the real and virtual sessions, as well as the high and low stiffness blocks was randomized and counterbalanced across all subjects. Every block was composed of 40 randomized trials, with 20 trials using soft objects and 20 trials using hard objects. The first 10 trials of each block were separately randomized and balanced, forming a dedicated familiarization block within the data. In addition, every block was preceded by a familiarization session, in which the subjects were aware of which objects they were interacting with, and allowed to explore them at will. In between each block, every subject took a short break of 3-5 minutes.

During each trial, a single object was placed or simulated in the PS gripper and the subject was asked to compress it, and determine its stiffness (low or high) based on the force feedback received. Once the subject made the determination, they pressed the corresponding input button on the keyboard, and the trial ended. During real object sessions, the subject was verbally instructed to sit back in a relaxed posture and wait while the object was physically removed from the gripper, and then either switched out or replaced back into the gripper. The subject was then verbally instructed to resume trials. During virtual object blocks, the objects were automatically cycled through after the subject recorded a response and moved back to a neutral posture, resetting the gripper. Data collected during the trial included decision time, defined as the time between the initial contact with the subject and the PS, blocking their view of the gripper and allowing the subject to explore them at will. In between each block, every subject took a short break of 3-5 minutes.

C. Subjects

A total of 8 subjects participated in Experiment 1, 5 females and 3 males. All subjects were right hand dominant. A total of 12 subjects participated in Experiment 2, 2 females and 10 males. All subjects, except for one, were right hand dominant. All experimental procedures were reviewed by the Colorado School of Mines Internal Review Board, and informed consent was given by all participants.

III. RESULTS AND DISCUSSION

A. Experiment 1 Results

For all subjects, the first 10 trials (training) of each block were dropped from analysis as discussed above. The statistical analysis of the decision time data set is complicated by the presence of an anomaly in data for S7. During the real object data collection session of this subject, the PS device mechanically failed when attempting to collect data at the $K_D^+$ device stiffness setting. The decision was made to ask S7 to repeat the session, effectively doubling the subject’s experience at that particular device setting. In the final analysis, S7 was the only subject to demonstrate a faster
decision time at the $K_{D}^+$ setting when compared to the $K_{D}^-$ setting, and only in the real object condition. It is reasonable to conclude that the additional experience significantly improved the performance of S7 at the $K_{D}^+$ condition with real objects. Therefore, data for S7 was excluded from statistical analysis, based on objective circumstances. Table I below summarizes the average decision times for the remaining seven subjects in all conditions during the first experiment.

The decision time data were subjected to a two-way repeated measures analysis of variance, with the factors being the two device stiffness settings ($K_{D}^+$ and $K_{D}^-$), and the two object types (real and virtual). The significance threshold for all statistical tests was set at $p < 0.05$. The main effect of device stiffness on decision time resulted in an $F$ ratio of $F(1, 6) = 8.39, p = 0.027$, indicating a statistically significant decrease in decision time when subjects were using a low stiffness device. The main effect of object type on decision times produced an $F$ ratio of $F(1, 6) = 5.33, p = 0.06$, indicating that the difference in decision times for real and virtual objects was not statistically significant. The interaction effect was non-significant, $F(1, 6) = 0.01, p = 0.91$. Including the data of S7 in the analysis results in a meaningful change only in the main effect of device stiffness, with the intact eight subject data set producing an $F$ ratio of $F(1, 7) = 4.34, p = 0.075$. As discussed above, objective considerations point to S7 as an outlier in the data set.

The impact of device stiffness on decision time was confirmed as significant by one-way repeated measures analysis of variance applied to the reduced real and virtual object data sets individually, with $p = 0.027$ and $p = 0.031$ respectively. Similarly, when examined individually the subjects’ decision time was not significantly affected by the type of object, real or virtual, they were interacting with ($p = 0.19$ at the high stiffness setting, and $p = 0.058$ at the low device stiffness setting).

Table II summarizes the error rates for all conditions during Experiment 1.

The error data trends are less clear, with real objects showing a small increase in error rates at the low stiffness setting, while the virtual object data indicate a marked decrease in errors. To trace the source of this discrepancy, the error rates were broken down by subject, and the results are presented in Table III.

**B. Experiment 1 Discussion**

The initial experiment provides support for the hypothesis that low end effector stiffness results in improved performance when attempting to distinguish between objects based on their stiffness. At the low stiffness setting, the users identified objects faster, and in the case of virtual objects, demonstrated a significant decrease in error rate as well.

No significant difference was found between the subjects’ decision times when interacting with real and virtual objects, indicating the potential to remove physical springs from further experiments without compromising the applicability of the results.

The error results are less uniform, with 4 out of 7 subjects showing an increase in the error rate when using a low stiffness device to interact with real objects. Conversely, 6 out 7 subjects demonstrate a noticeable decrease in error rate when interacting with virtual objects using a low stiffness device compared to a high stiffness device. This may be explained by the fact that while the use of virtual objects left the entire 90° travel arc of the gripper unobstructed, the physical sponges inevitably took up some of that space. This reduced the amount of information the subjects received about the objects during a single contraction. In addition, while the physical objects responded in a linear fashion during initial compression, after a sufficient deflection, the response becomes non-linear (demonstrating a hardening spring behavior), as more and more sponge material is squeezed into a smaller space. This effect occurs with both the hard and the soft sponge, increasing the similarity of their response at extreme gripper deflections, and may have contributed to the error rate trends.

The low stiffness virtual object condition appears to have been the easiest by far, with significantly shorter decision times, and error rates significantly lower than all other conditions. This is not unexpected, as the low stiffness of the device means that a greater percentage of the force displayed back to the subject is contributed by the object, and the

<table>
<thead>
<tr>
<th>Subject</th>
<th>Real Objects</th>
<th>Virtual Objects</th>
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<tbody>
<tr>
<td></td>
<td>$K_{D}^+$</td>
<td>$K_{D}^-$</td>
</tr>
<tr>
<td>1</td>
<td>33.3</td>
<td>13.3</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>5</td>
<td>30.0</td>
<td>73.3</td>
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<td>6</td>
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<td>7</td>
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virtual spring was a simplified linear approximation of the more complex response of the physical sponges.

Anecdotally, a significant majority of the study participants reported a preference for the lower end effector stiffness setting, without being aware of their relative performance. This indicates that prosthesis users may be able to optimize the stiffness settings of their devices to match the requirements of a particular task, given the mechanical capability and an intuitive interface.

C. Experiment 2 Results

Data from the first 12 (training) trials in every block for all subjects were dropped from further analysis, as discussed above. Table IV shows the average decision time during the second experiment.

A one-way repeated measures analysis of variance revealed no significant difference in the subjects’ performance at the three different device stiffness settings ($p = 0.40$).

Table V presents the error rates for all subjects in all conditions. It also contains the adjusted between-group error rates, obtained by ignoring errors within the soft and hard groups, i.e. not counting the instances in which subjects mistook the $K_3$ object for the $K_2$ object, or confused $K_3$ with $K_4$.

D. Experiment 2 Discussion

The results of Experiment 2 do not appear to follow or extend those of Experiment 1, with various device stiffness settings producing little to no impact on overall task performance. The results are profoundly undermined by the extremely high error rates, which are close to 50% across all conditions, indicating that subjects had great difficulty in identifying the correct object stiffness. The error rate of subjects using the lowest device stiffness setting in Experiment 1 and Experiment 2 shows an increase of over 10x!

Anecdotally, many subjects reported difficulties in keeping track of the relative stiffness of each of the four objects throughout the trial. A further look into the data showed that any potential effects from the stiffness settings were shadowed by learning effects, with decision times nearly uniformly high during each subjects first trial block, before dropping off in later trials. This suggests that the familiarization protocol built into each block was insufficient, requiring subjects to learn on the go, with no feedback or knowledge of results, which could have significantly increased error rates.

In summary, we concluded that the difficulty level of the task in Experiment 2 was not adjusted appropriately, which made it difficult to draw meaningful conclusions from the data. Nevertheless, the results of this experiment will inform design of future studies, which will take into account the issues uncovered. Particularly, object sets should be kept small, with subjects ideally required to make a simple binary choice. Also, familiarization procedures should also be expanded and improved in accordance with the difficulty level of the task.

IV. Conclusion

This study reinforces the importance of prehensor stiffness modulation in task performance by prosthesis users. It complements previous work in the area by (1) providing evidence for the importance of stiffness modulation in body-powered prostheses, and (2) demonstrating the impact of end effector stiffness on task performance for stiffness discrimination. Results of the first experiment indicated that performance of prosthesis users in a stiffness discrimination task can be improved by proper modulation of device stiffness.

V. Acknowledgements

We gratefully acknowledge the assistance of Jeremy F. Guiley in developing code for both human subject experiments.

REFERENCES


