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Grip Force Control Using Prosthetic and Anatomical Limbs

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INTRODUCTION

Healthy adults are remarkably adept at manipulating a diversity of objects, adjusting grip forces to various object properties with limited conscious awareness of the properties themselves or the actual adjustments that are made in response to those properties. For example, when an object is held unsupported in space by the anatomical hand, grip forces are subconsciously adjusted according to the object's weight[1–4] and surface friction.[5, 6] However, due to the lack of afferent sensory modalities within the prehensor itself, this constant calibration may be lacking for upper-limb prosthesis users.

Tactile sensory feedback from the skin of the grasping fingertips of the anatomical hand plays a crucial role in the automatic control of prehensile finger forces, providing real time sensory feedback about changes in inertial loads and the stability of the interface between the skin surface and the object as the object is held or transported.[1–4, 7, 8] Tactile skin receptors signal important information about movement related events, including that the object has been contacted or that it has started to move or to slip from the grasp. The importance of tactile sensory information in fine manipulative movements is supported by the problems commonly experienced by persons with impaired manual sensibility who frequently drop objects, easily crush fragile objects, and have problems performing simple activities of daily living like buttoning a shirt when dressing.[9–11] Such observations led Moberg (1975) to claim that reconstructive surgery of the hand should aim to preserve all possible cutaneous innervation because the smallest grip with sensibility is preferable to the best hand prosthesis.

Research on grip force control with the anatomical hand suggests that cutaneous sensory cues are important for modulating force when manipulating an object. Upper-limb prosthesis users are not able to take advantage of sensory cures to modulate force when manipulating an object, at least at the level of the hand. If, as suggested by contemporary researchers, effective grip force regulation during object manipulation results from an internal model that

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is updated by peripheral sensory information, then the person with amputation has two major limitations that will reciprocally influence each other. First, during the early stages of skill acquisition with their new prosthesis, the person with amputation will not have an accurate internal model of interactions among limb dynamics, object properties, and task constraints to specify appropriate neural commands to the body parts that control the prosthesis and its prehensor. Second, the person with amputation will lack the cutaneous sensibility at the prehensor, which is needed to pick up real time information about changes in the inertial characteristics of the object and potential changes at the interface between the object surface and the grasping surface of the prehensor as the object is held or moved around. Ultimately, the lack of cutaneous sensibility could significantly retard or even prevent the development of effective internal models for grip force regulation during object manipulation.

Though accurate statistics are illusive, by some conservative estimates there are over 100,000 people with upper-limb amputations in the United States.[12, 13] However, the Amputee Coalition[14] in conjunction with the National Limb Loss Resource Center[15] compiled statistics that suggest the number of individuals with upper-limb amputations may exceed prior assumptions. Most upper-limb amputations are below elbow, and a greater percentage of people with amputations use body powered artificial limbs, as opposed to externally powered prostheses such as myoelectrically controlled devices.[16]

Two types of prehensors, which function in an inverse manner relative to each other, are typically used with the body powered prosthesis. The voluntary opening (VO) device is naturally closed and requires an increase of cable tension to open. The voluntary closing (VC) device is naturally open and requires an increase of cable tension to close. A recent study investigated the functionality and preference of users of the VO and VC prehensors in a validated test of activities of daily living.[20]. The results of the study indicated that the VC device allowed task completion to be 1.3 sec faster on average than the VO, although no clear differences in functionality were observed. Some participants preferred to use the VC, while others preferred the VO, depending on the type of task. Some participants expressed concern that the VO lacked sufficient grip force in some activities. This limitation is due to the fact the maximum grip force in the VO prehensor is determined by the strength of the rubber bands that are used to close the prehensor. Interestingly, most participants commented that it was more difficult to perceive the force they were applying to an object using the VO prehensor compared to the VC. One possible explanation for this finding is that participants need to decrease the effort they use when applying force to an object with the VO prehensor, whereas they do just the opposite with the VC prehensor. The different relation between muscle tension and grip force has been discussed previously relative to the notion of compatibility. Based upon a large literature on stimulus-response (S-R)[21] and response-response (R-R)[22] compatibility in the psychological and motor control literature, as well as observations from others in the field of prosthetics,[23–26] it has been suggested that the relation between muscular tension and grip force may be less intuitive in the VO prehensor than the VC prehensor, at least for new prosthesis users.[27] Because of the lack of direct sensory feedback from the prehensors (there are no force receptors on the prehensors), grip force is not directly fed back to the user. Rather, the user perceives grip force indirectly from the muscle tension used to apply the force. Thus it would seem that the relationship between the muscle tension used and the resulting changes in prehensor grip force should be intuitive to maximize performance.

The use of a bicycle brake analogy helps describe this type of intuitive relationship or compatibility. To brake a bicycle, the bicyclist applies grip force, causing an increase in the tension on the brake cable and the brake pads to close, slowing down or stopping the bicycle. This operation represents a positive correlation, and possibly an intuitive or logical compatibility between grip force and brake force. The VC prehensor shares this type of compatibility because generating muscle force by body motions increases tension on the cable that connects the shoulder harness system and the prehensor, causing prehensor grip force to increase. The correlation between muscle tension and grip force is positive in the VC prehensor. In contrast, the correlation between muscle tension and prehensor grip force in the VO prehensor is negative because to increase prehensor grip force, the user must *reduce* cable tension by body motions. Consequently, the VO and VC prehensors might be suited to different types of tasks.[27]

To examine this idea, we previously conducted a case study with a person having congenital, quadruple amputations who uses both upper- and lower-limb prostheses on all four limbs.[28] This individual was an experienced prostheses user who only used body-powered upper-limb VO prehensors for both right and left limbs and who had no previous experience with a voluntary closing prehensor. The unique manipulation in this study was that we asked our participant to perform a grip force control task, similar to the one used in the current study, with his own VO prosthesis and also with a VC prosthesis that he had never used before. On some measures of grip force control, the participant actually performed better with the unfamiliar VC prosthesis.

To further examine this hypothesis, in the present experiment we asked a group of participants without amputation to perform a similar grip force task using an upper-limb body powered prosthetic simulator[29] that mimics the functionality of a typical body powered prosthesis used by people with amputations. Participants performed the grip force control task with the VO and VC prehensors fixed to the prosthetic simulator with and without augmented visual feedback of the target forces they were asked to produce. We wished to determine whether the predicted effects of muscle tension-grip force compatibility would be present with and without augmented visual feedback. The augmented visual feedback was initially provided to help the participant produce the required grip force and then it was removed to see if the participant could maintain the level of grip force.

Based on the prior research with the experienced prosthesis user, we predicted that participants would produce the target force more accurately and with less variability when they used the VC prehensor compared to the VO prehensor. In addition, we expected that due to experience, performance with the anatomical hand would be superior to performance with the VO and VC prehensors.

MATERIALS AND METHODS

Participants

Ten able-bodied individuals (average age 22±4 years of age, five male and five female) participated in the study. Eight participants were right hand dominant, and two participants were left hand dominant. All participants gave informed written consent for this study that was approved by the institutional review board at San Francisco State University.

Apparatus

Grip force was measured using Biopac MP30 Hardware for Biopac Student Laboratory Pro software along with the Biopac Systems hand dynamo set at a sampling rate of 500 samples per second. The hand dynamo was placed on a wooden platform that allowed the dynamo to stand erect in a locality that was comfortable for the participant to grasp. The volunteer was situated so that he/she could grasp the dynamo with the terminal device of the prosthetic simulator, which was projected forward in the sagittal plane (Figure 3). A force output tracing was displayed on a 16-inch monitor that was placed approximately one meter away from where the participant sat upon a stationary chair. The body-powered prosthetic simulator, developed in-house, could be equipped with either a Sierra 2-Load VO hook (Hosmer Dorrance Corp; Campbell, California) or an APRL VC hook (Hosmer Dorrance Corp) and utilized a cable-harnessing system identical to an actual prosthesis. Two simulators, one for left and one for right hand dominant participants, were utilized.

Procedures

Before the participant sat down to perform the experiment, he/she watched an informational video created by our research team. The video consisted of a demonstration and commentary describing how terminal device manipulation was accomplished through manipulation of cable tension. The informational video demonstrated in an explicit manner the difference between the two types of terminal devices and what actions would open or close each device. The participant was then asked if he/she understood how to increase, decrease, and control grip force with both devices. All participants confirmed that the instructional video provided sufficient explanation for prehensor control. The experimental protocol was then read to the participants and they were asked if they were ready to begin.

After viewing the demonstration video and confirming readiness, the volunteer donned the prosthetic simulator on their dominant side with help from the experimenter. The participant was situated in a chair so that he/she could comfortably grasp the hand dynamo. Three practice trials were given before the experiment began. Each participant received practice with the VO, anatomical hand (AH), and VC in that order. In the practice trials, the participants produced grip forces of 1 Newton (N), 5N, and 12N all with the use of vision. The participants were then informed that they were about to begin the 54 trial protocol and asked if they were ready to begin. After confirmation, the experimental protocol began.

Each trial lasted for a total of 15 seconds. In the experimental trials, the participant was given 5 seconds from the start of each trial to reach the target grip force with the aid of augmented visual feedback by manipulating grip force on the dynamometer. He/she was then asked to sustain the target grip force for 10 seconds on each trial. In the *no augmented visual feedback* condition, visual feedback was manipulated by covering the monitor screen during the last 10 seconds of the trial. In the *augmented visual feedback* condition, the monitor was uncovered during the last 10 seconds of the trial. We believed that this type of grip force task, similar to the one used previously,[28] would allow us to adequately examine the hypothesis under different visual feedback conditions. This type of task has commonly been used to study the control of grip forces during grasping, to identify the brain areas involved in the regulation of grip forces, and to measure deficits in grip force control in patients with various central nervous system pathologies.[29]

Design

The experiment consisted of a 3 × 2 × 3 (hand condition × augmented visual feedback condition × target force) design. Hand condition consisted of performing the target grip force task with the VO prehensor, the VC prehensor, and the anatomical hand. Augmented visual feedback condition consisted of performing the target grip force task with or without augmented visual feedback for the last 10 seconds of each trial. The target force conditions were either .49, 4 or 10.5 N. Each unique hand condition, augmented visual feedback condition and target force condition was repeated three times in a row for a total of 54 trials. Intertrial interval was approximately 15 seconds. The participants fell into one of two groups. The first group, n = 5, performed all conditions with the VC split hook, then the AH, then the VO. The second group, n = 5, performed all conditions with the VO, then the AH, then the VC. Unfortunately, the data for three subjects were compromised because of a hardware malfunction. The second and tertiary conditions were randomized for each hand condition. For example, the presence or absence of augmented visual feedback as well as force variables was randomized. After all 18 trials were completed for each hand condition the participant was given an opportunity to rest before continuing testing with the next effector protocol. The fatigue effect was reduced by interceding the two simulator conditions with the AH condition.

RESULTS

Three measures of grip force accuracy and variability were assessed for each condition. Absolute constant error is a measure of accuracy and is defined as the absolute value of the difference between the target force and the force output. Variable error is a measure of variability and is defined as the standard deviation in the difference between target force and force output. Biasing index (BI) is a measure that quantifies the degree to which the participant overshot or undershot the target and can provide more details of the types of grip force errors the participant can make. BI is calculated as:

$$\mathrm{BI} = (\mathrm{under} - \mathrm{over}) / (\mathrm{under} + \mathrm{over})$$

BI has a range of −1 to 1 and values greater than 0 indicate a bias toward overshooting a target force and values less than 0 indicate a bias toward undershooting a target force. For example, if the participant consistently exerted either too little or too much grip force relative to the target force over a set of trials, the biasing index would be significantly less or greater than zero, respectively.

A one-way ANOVA was performed for each force × vision condition to assess performance differences for each condition. The primary question we wanted to answer was how each prosthetic prehensor (VO vs VC) performed relative to each other as well as to the anatomical hand in producing a target grip force both with and without augmented visual feedback.

Absolute Constant Error

For absolute constant error, larger values indicate less accuracy and lower values represent greater accuracy. Figure 4 represents mean plus standard error measure for the absolute constant error for each force × augmented visual feedback condition. One observation gleaned from this figure is that errors in the no-augmented visual feedback conditions (bottom panel) are generally larger than under augmented visual feedback conditions (top panel). Please note that the vertical scale (in Newtons) is much smaller for the augmented visual feedback condition graphs than for the no-augmented visual feedback condition graphs. This result clearly points to the importance of augmented visual feedback for this type of task requiring the matching of actual grip force to the target grip force. The augmented visual feedback clearly provided information that facilitated error detection and correction.

In addition, closer inspection reveals that, particularly in the no-augmented visual feedback conditions, the pattern of errors for the AH and VC are more similar than for the AH and the VO. Generally, for the AH and VC conditions, errors increase as the target forces increase. However, for the VO condition, errors *decrease* as the target force increases.

While the absolute constant errors were very small in the augmented visual feedback condition, a one-way within condition analysis of variance (ANOVA) revealed a significant difference in absolute constant error for the 4N [$F(2, 60) = 3.73$, $p < 0.05$] and 10.5N [$F(2, 60) = 6.8$, $p < 0.05$] augmented visual feedback conditions, as well as the 0.49N [$F(2, 60) = 9.02$, $p < 0.001$] and 10.5N [$F(2, 60) = 4.7$, $p < 0.05$] no-augmented visual feedback conditions. A Tukey’s honestly significant difference post-hoc test revealed that the VO prehensor was significantly less accurate than the VO and AH for the 4N target force with augmented visual feedback. In addition, the AH was significantly less accurate than both the VO and VC for the 10.5N target force with augmented visual feedback.

Without augmented visual feedback, the VO prehensor was less accurate than both the AH and VC for the 0.49N target, but the AH was significantly less accurate than the VO for the 10.5N target force.

Variable Error

Higher variable error means more variability in performance and lower variable error represents more consistency in performance. Similar to absolute constant error, variable errors were generally higher in the no-augmented visual feedback compared to the augmented visual feedback conditions. In addition, the patterning of errors, particularly in the no-augmented visual feedback conditions were more similar for the AH and VC conditions compared to the AH and VO conditions.

Figure 5 represents mean plus standard error measure for the variable error for each force × augmented visual feedback condition. A one-way within condition ANOVA revealed a difference in variable error for the 0.49N [$F(2, 60) = 4.6$, $p < 0.05$] and 10.5N [$F(2, 60) = 6.18$, $p < 0.01$] target forces with augmented visual feedback as well as the 0.49N [$F(2, 60) = 12.44$, $p < 0.001$], 4N [$F(2, 60) = 3.71$, $p < 0.05$], and 10.5N [$F(2, 60) = 7.12$, $p < 0.01$] target forces without augmented visual feedback. A Tukey's honestly significant difference post-hoc test revealed that the VO was significantly more variable for the low force condition (0.49N) with augmented visual feedback. The AH was significantly more variable than both the VC and VO condition for the high target force (10.5N) with augmented visual feedback.

Without augmented visual feedback, the VO was significantly more variable than both the AH and VC for the 0.49N condition. The VO was also more variable than the VC for the 4N condition. The AH was significantly more variable than both the VC and VO for the 10.5N target force condition.

Biasing Index

Figure 6 represents mean plus and minus standard error measure for biasing index. A one-way within condition ANOVA revealed a difference in biasing index for the 4N [$F(2, 60) = 17.53$, $p < 0.001$] and 10.5N [$F(2, 60) = 9.24$, $p < 0.001$] target force with augmented visual feedback and 4N [$F(2, 60) = 13.19$, $p < 0.001$] and 10.5N [$F(2, 60) = 7.03$, $p < 0.005$] target force without augmented visual feedback. A Tukey's honestly significant difference post-hoc test revealed that both the VO and VC overshot the 4N target force with augmented visual feedback, but the AH slightly undershot the target force. The VO overshot the target more than the VC and the VC and AH were more similar. For the 10.5N target force with augmented visual feedback, both the AH and VC undershot the target on average, but the VO was closer to the target than both the VC and AH.

For the no-augmented visual feedback conditions, both the AH and VC undershot the target for the 4N target force, but the VO overshot the target. For the 10.5N target force, all three prehensors undershot the target force on average. It should be noted that the only difference between the VC and AH was for the 4N target force with augmented visual feedback. These results indicate that the trend towards undershooting and undershooting the target is the same for the AH and VC.

DISCUSSION

The purpose of the present study was to assess the accuracy and variability of grip force control using a VO and VC prehensor and the anatomical hand. Participants were given augmented visual feedback initially to help them produce the target force and then the augmented visual feedback was either maintained or removed to assess how well the target force could be maintained. Our results indicated that when augmented visual feedback was available, there were little accuracy and variability differences in the types of prehensor used in the grip force task, even though some statistically significant differences between the conditions occurred. The accuracy and variability differences between the prehensor conditions were less than .3 and .5 N, respectively. We would interpret these results by saying that when augmented visual feedback is available, no meaningful performance differences occurred between the prehensors. This result suggests that visual feedback might be used to overcome any limitations of the prehensors. Augmented visual feedback allows the participant to compare their exerted grip force with the target grip force on the computer monitor so that any discrepancies between them can be corrected. This type of knowledge of results has been shown to be a powerful type of feedback for skill acquisition .[30] So, when augmented visual feedback was available, there were no meaningful performance differences between the two prehensors. However, it is important to note that when objects are lifted, held, and manipulated during activities of daily living, this type of feedback is not available. A person has to rely instead on intrinsic feedback provided by the proprioceptive system to maintain and adapt grip forces applied to an object.

When augmented visual feedback was removed, there were several indications that performance accuracy and variability were affected by the type of prehensor and the level of the target force. In general, and as expected, errors were greater when augmented visual feedback was unavailable. As just noted, participants needed to rely upon intrinsic feedback provided by the proprioceptive system and compare this feedback with a memory representation of the target force. With inexperienced users, it was likely that the memory of the target force based upon proprioception was relatively weak. Thus, after augmented visual feedback was removed after 5 sec at the beginning of the trial, the participant must have tried to compare current proprioceptive feedback with a perceptual memory of the target force. Since the target force memory was likely relatively weak, and with no augmented visual feedback to rely upon, performance suffered. In general, accuracy and variability was similar for the VC and anatomical hand conditions. At the .49 and 4 N target force conditions, the VC and anatomical hand conditions showed more accurate and less variable performance than the VO condition. However, at the 10.5 N target condition, the VO condition was more accurate and less variable than the VC and anatomical hand conditions. How might this result be explained?

One well-known relationship in the area of human motor control is the force-force variability relationship.[31] In general, it has been found that the variability of producing muscular force increases as target force increases, while the exact nature of these increases (i.e., linear, exponential) has been debated.[32, 33] Can the force-force variability relationship provide an explanation of some of the results of the present study? If so, we would expect that as the target force increased, the variability of the grip force production using the VO, VC prehensors and anatomical hand should have also increased. In general, our results are fairly consistent with the force-force variability relationship. However, it is important to make a distinction between the prehensor grip force and the muscular tension used to produce that force within the context of the present study. As discussed previously, with the VC and anatomical hand, an increase in muscular tension produces an increase in prehensor (or finger) grip force. Therefore, according to the force-force relationship, variability of grip forces should increase as the target grip force increases. As seen in Figure 5 (bottom panel), this result was observed, particularly in the absence of augmented visual feedback. However, in the VO condition, the target force-grip force variability relationship was effectively reversed. Figure 5 (bottom panel) shows that for the VO condition, the largest variable error was produced in the .49 N target force condition. One explanation is that even though .49 N was the smallest target force, greater *muscular* tension was necessary when using the VO prehensor. So, what contributed to performance variability was not the target force per se but the amount of muscle activity used to control the prehensor. This result could be further evaluated in future studies that examine the relationship between grip force control (and performance on various ADL tasks), and the type of muscle groups used to control cable tension in body-powered prostheses.

Another interesting result was that at the larger target force condition (10.5 N), performance with the anatomical hand was actually *inferior* to the two prostheses conditions. This result could also be explained by the force-force variability hypothesis because the muscles that control grip force in the anatomical hand are relatively smaller and weaker than those that control grip force in the prehensors (trunk and shoulder muscles). Consequently, the muscles of the anatomical hand must work at a higher relative intensity than those used to control the prehensors and thus would be expected to generate greater variability. Alternately, the superiority of the prehensors could be because of the dynamics of the cabling system. Future investigations could examine the type of oscillations produced by the VO and VC prehensor compared to the anatomical hand. Anatomical hand grip force oscillations have been shown to increase with advancing age[34] and with certain neurological disorders.[35] But there is virtually nothing known about oscillations produced by prostheses and little is known whether grip force oscillations are affected by the type of prehensor (VO vs VC, body-powered vs EMG powered), or muscle groups being activated, for example. Clearly much more work is needed to understand the advantages and disadvantages of using the VO and VC prehensors relative to each other and relative to the anatomical hand.

And lastly, while we feel the type of task used in the present study provided some insight into how grip pressure is regulated by different types of prehensors, more work needs to be done on whether muscle tension-grip force compatibility influences performance on different ADL tasks. This work could lead to advancing our knowledge of the strengths and limitations of the VO and VC prehensor and assist the occupational therapist in improving prosthesis training.

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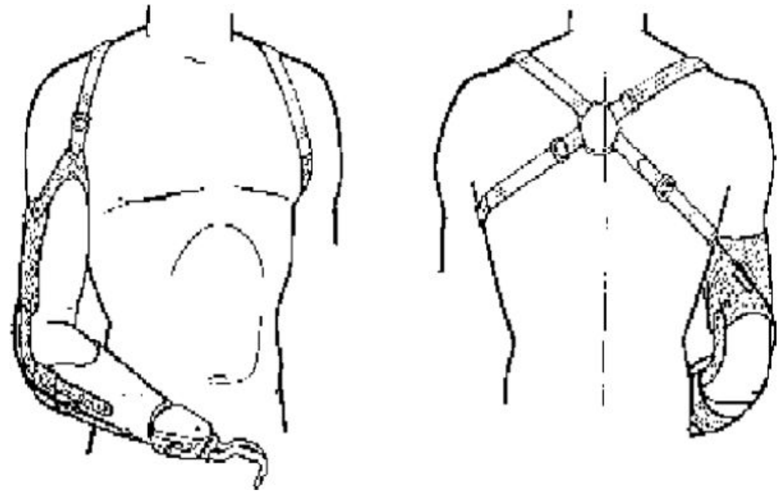

Figure 1.
Prosthetic limb.

Figure 2.
Prosthetic simulator.

Figure 3.
Experimental setup.

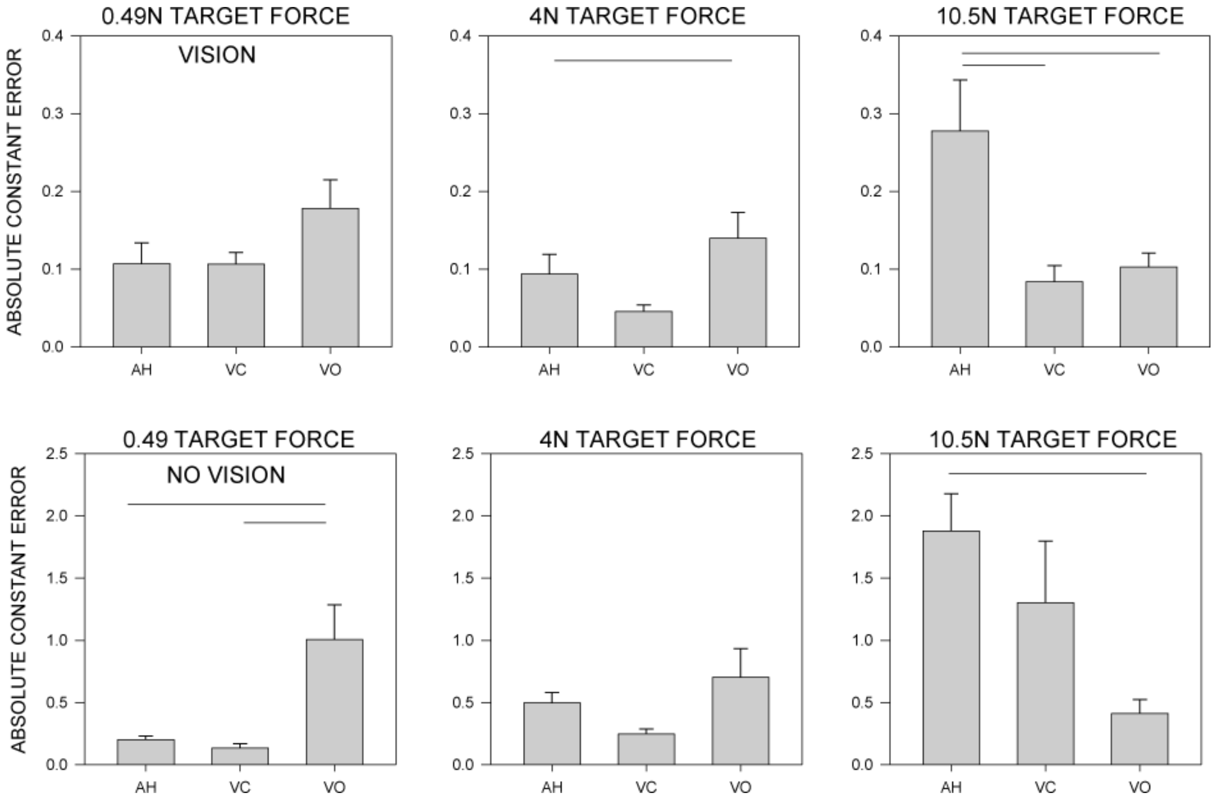

Figure 4.

Mean plus standard error measure for absolute constant error. Along the horizontal axis are the three prehensor conditions: Anatomical hand (AH), voluntary closing (VC), and voluntary opening (VO). The three target forces of .49, 4 and 10 N are shown from left to right. On the top panel is the vision condition (with augmented visual feedback) and on the bottom panel is the no-vision condition (without augmented visual feedback). Notice that the scales of the augmented and without augmented visual feedback conditions are different. A one-way ANOVA revealed a significant difference in the average absolute conference error for the 4N and 10.5N vision conditions, as well as the 0.49N and 10.5N no-vision conditions. The horizontal lines within each panel represent a statistical difference between prehensors as revealed by a Tukey's honestly significant difference post-hoc test.

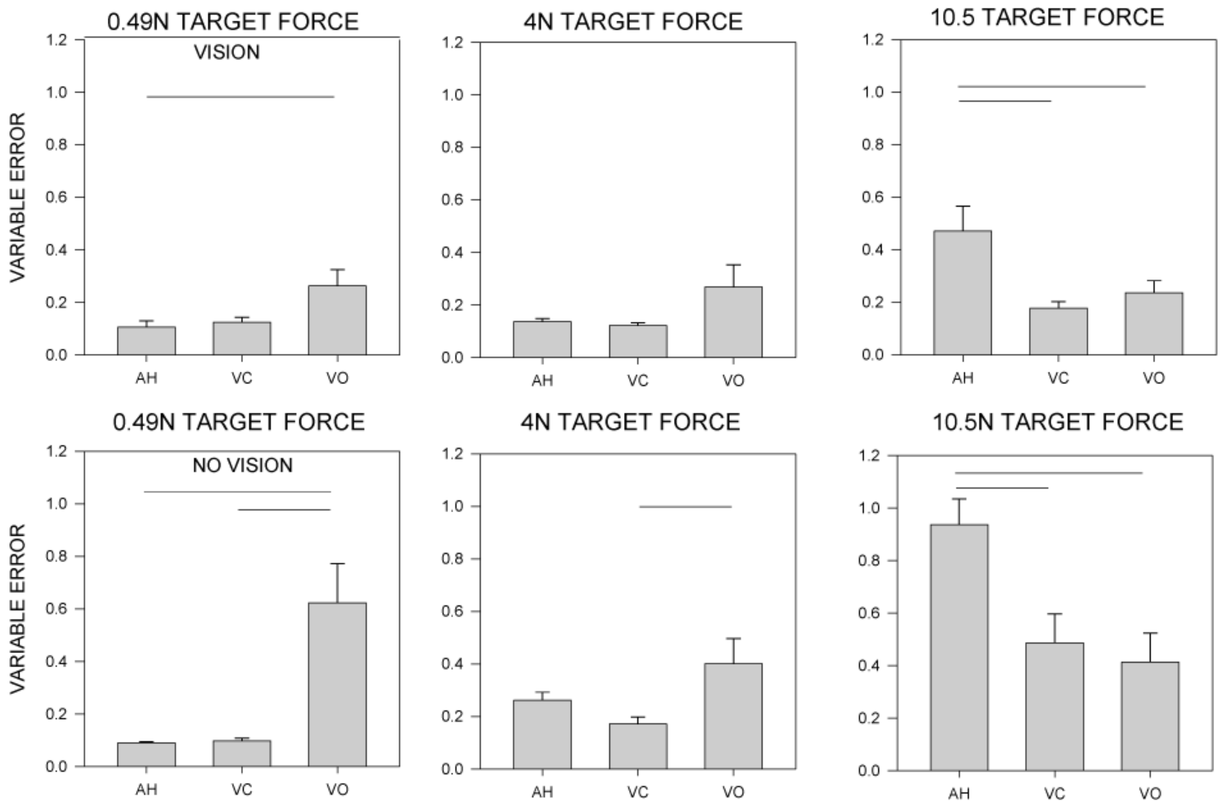

Figure 5.

Mean plus standard error measure for variable error. Along the horizontal axis are the three prehensor conditions: Anatomical hand (AH), voluntary closing (VC), and voluntary opening (VO). The three target forces of .49, 4 and 10 N are shown from left to right. On the top panel is the vision condition (with augmented visual feedback) and on the bottom panel is the no-vision condition (without augmented visual feedback). Notice that the scales of the augmented and without augmented visual feedback conditions are different. A one-way ANOVA revealed a significant difference in the average absolute conference error for the 0.49N and 10.5N vision conditions, as well as the 0.49N, 4N and 10.5N no-vision conditions. The horizontal lines within each panel represent a statistical difference between prehensors as revealed by a Tukey's honestly significant difference post-hoc test.

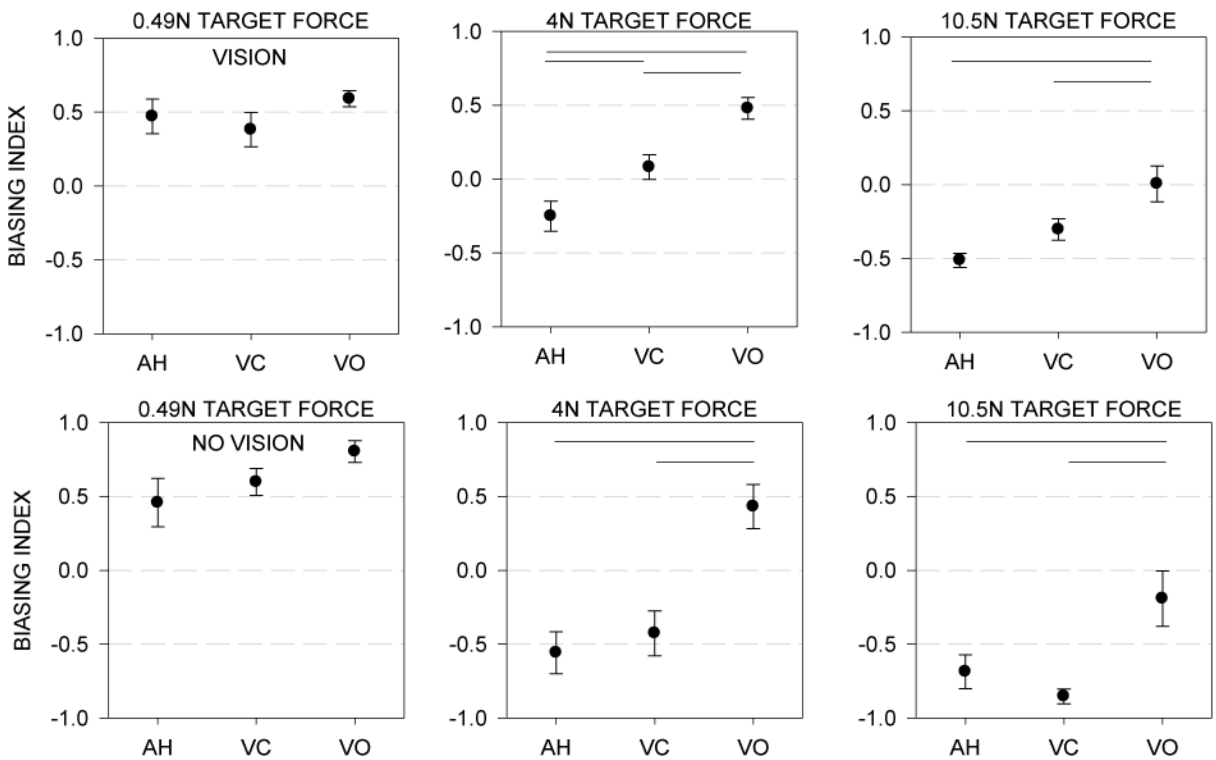

Figure 6.

Mean plus and minus standard error measure for biasing index. Along the horizontal axis are the three prehensor conditions: Anatomical hand (AH), voluntary closing (VC), and voluntary opening (VO). The three target forces of .49, 4 and 10 N are shown from left to right. On the top panel is the vision condition (with augmented visual feedback) and on the bottom panel is the no-vision condition (without augmented visual feedback). Notice that the scales of the augmented and without augmented visual feedback conditions are the same. A one-way ANOVA revealed a significant difference in the average absolute conference error for the 4N and 10.5N for both the vision and no-vision conditions. The horizontal lines within each panel represent a statistical difference between prehensors as revealed by a Tukey's honestly significant difference post-hoc test.