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Effect of variable transmission on body-powered prosthetic grasping

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***Abstract*— Body-powered upper-limb prostheses remain a popular option for those with limb absence due to their passive nature. These devices typically feature a constant transmission ratio between the forces input by the user and the grasp forces output by the prosthetic gripper. Work incorporating continuously variable transmissions into robotic hands has demonstrated a number of benefits in terms of their motion and forces. In this work, we use a custom prosthesis emulator to evaluate the viability of applying variable transmissions to a body-powered prosthetic context. With this haptics test bed, we measured user performance during a grasping and lift task under a variety of transmission ratio conditions and with three different test objects. Results indicate that use of a variable transmission leads to the successful manipulation of a wider variety of objects than the constant transmission ratio systems, while requiring less shoulder motion. Analysis also shows a potential tendency for users to apply higher grasp forces than necessary, when compared to constant transmission conditions. These findings suggest a multifaceted effect on grasp performance with both benefits and drawbacks when considering a variable approach that supports the continued study of variable transmissions in assisted grasping.**

I. Introduction

Body-powered upper-limb prostheses often use a Bowden cable and harness worn on the contralateral shoulder to mechanically link the force and motion of the user's body to that of the end-effector, in a control topology known as extended physiological proprioception (EPP) [1]. As compared with more complex myoelectric devices, recent studies show body-powered prosthesis users use their devices more often and with shorter grasp duration [2], as well as exhibit improved performance on aperture sizing, stiffness discrimination, and target tracing tasks [3], [4]. However, user surveys demonstrate a lack of satisfaction with current body-powered devices [5] and indicate the desire for a reduction in effort to operate body-powered devices [6].

Within the class of shoulder-driven body-powered prostheses, grippers are controlled through glenohumeral flexion and scapular protraction through the shoulder harness, and operate in either voluntary opening (VO) or voluntary closing (VC) styles. Applying cable force to a VO device opens the gripper and a set of elastic bands applies the grasp force, while applying force to a VC device closes the gripper to apply grasp force and a restorative spring returns the gripper to its open state. In functional tests, VC prostheses demonstrate improved task performance rate and perceived feedback [7]. Our research goal is to maintain these benefits while mitigating the inherent drawbacks of body-powered VC grasping through new transmission designs.

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There is a video supplement associated with this work.

TABLE I
Comparison of Transmission Ratios

	Low R	**High R**
Grasp Force	Low	High
Haptic Feedback	High	Low
Cable Excursion	Low	High
Suitable Objects	Small, Light	Large, Heavy

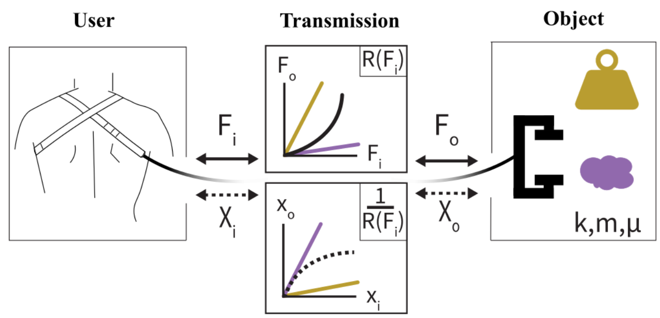

Fig. 1. The introduction of a force-sensitive continuously variable transmission to a body-powered prosthesis can improve grasp performance of a variety of objects. By adjusting its transmission ratio R based on input forces F_i, variable transmission prostheses (black) can enhance end effector travel x_o at low forces for small and light objects (violet) and amplify output grasp forces F_o at high forces for large and heavy objects (gold). Demonstrative force (top) and excursion (bottom) plots illustrate how low ratio fixed transmission devices (violet) exhibit efficient travel but low force output and high ratio fixed transmission devices (gold) exhibit high force output but little end effector travel even for large user input travel x_i.

A. Transmissions in body-powered prosthetic end effectors

The transmission ratio R – defined here as the ratio of grasp output force F_o to user input force F_i of a given VC prosthesis – is typically constant, fixed by the geometry of the cable-driven gripper. Resulting forces and travel of the cable Δx vary as:

$$R = \frac{F_o}{F_i} = \frac{\Delta x_i}{\Delta x_o}. \quad (1)$$

A higher transmission ratio device amplifies the output grasp force for a given user force input, desirable for grasping heavy or slippery objects, at the cost of additional required cable travel. With the shoulder's limited range of motion, grasping small or thin objects needing a small aperture to manipulate requires the user to contort into awkward postures at or near the limits of their range of motion, as was seen in [8]. High R devices present less force feedback to the user, which results in excessive grasp forces [9] that create the risk of crushing fragile objects.

Conversely, a lower transmission ratio device provides more gripper motion with less shoulder movement while reducing maximum grip force. Higher loads applied to users' bodies diminish their pinch force control [10], fatigue users, and cause discomfort at the harness site [11]. Despite these outcomes, a low transmission ratio can provide better communication of haptic contact cues [12]. The benefits and drawbacks of each end of the transmission ratio spectrum are summarized in Table I.

B. Variable transmission for grasping

Frey et al. (1994) introduce a variable mechanical advantage prehensor [8] in order to achieve fast yet strong grasping. By employing a toggling mechanism, the closing prehensor maintains a low transmission ratio until contact with an object, at which point the mechanism transitions into a new higher mechanical advantage mode. Because of the greater cable excursion demands, the test subject reports that they could not grasp "very soft objects...such as folded towels or rolled newspapers," as they were unable to produce sufficient shoulder motion [8]. We posit that the specific discrete and fixed transition implemented in this prior work amplified this issue. In the present study, we explore continuously variable transmissions (CVT) to study the effect of variable transmission on grasp performance.

CVTs, with gradual force-based changes, have been developed for a diverse set of applications from automobiles and bicycles to robotics and upper-limb prostheses. Within prosthetics, they have found use in both the elbow joint [13] and more often in robotic manipulators as a way to continuously transition between speed and force output of the actuator. Lightweight cable-based CVT typologies include the one by Matsushita et al. (2009) [14] and the Elastomeric Passive Transmission (EPT) [15]. These utilize a compliant tendon-drum that deforms under load for greater cable speeds at low tension forces and greater torque at higher tensions.

We evaluate the viability of a Variable Transmission Prosthesis (VTP), a voluntary closing upper-limb prosthesis which can change its transmission ratio continuously based on the forces it applies, outlined in Fig. 1. The system begins with a low transmission ratio to close the gripper quickly with minimal shoulder movement and amplify force feedback cues at initial contact. As the user applies additional load, the transmission ratio increases such that grasp force is amplified. In this manner, the user obtains the benefits of both low and high R devices: low transmission ratio at low grasp forces and high transmission ratio at high grasp forces. We hypothesize that this continuously variable transmission scheme reduces the force and motion required of the user while improving grasping performance across a range of objects as compared with a constant transmission. This work represents the first study exploring the integration of a CVT with a body-powered prosthesis for grasping.

C. Overview

In Sec. II, we describe the pilot human subjects experiment employed in this study where subjects use a haptic test bed to grasp demonstrative simulated objects under a range of constant and variable transmission models. Results presented in Sec. III show that variable transmissions improve the rate of successful grasps across different test objects, decrease required motions of the user, and increase applied grasp forces. In Sec. IV, we discuss the implications of the results for a fully integrated CVT in a physical body-powered prosthesis. Sec. V summarizes our findings and opportunities generated by this work to motivate future efforts.

II. Experimental Methods

To test the functionality of a variable transmission in body-powered prostheses, we replicate their applied forces and motion with a custom prosthesis emulator, detailed in [9]. This prior work uses the emulator to characterize grasp performance as force feedback applied through a shoulder harness changes; it does not simulate variable transmissions, changing excursion rates, nor varying object properties. In the current study, by evaluating grasp performance under different transmission conditions, we compare function with simulated variable transmissions to a range of constant transmission ratios.

A. Test bed implementation

The prosthesis emulator test bed, outlined in Fig. 2, comprises four primary subsystems: a shoulder harness, a height controller, a desktop haptic interface, and a virtual grasping environment displayed in an experimental graphical user interface (GUI). Shown in Fig. 2(a), the grasping environment contains visualizations of a test object (yellow) and two sides of an opposed gripper (grey). A Bowden cable connecting the haptic interface and the shoulder harness transmits force and position information between the interface and the user. Excursion of the cable controls the aperture of the gripper in

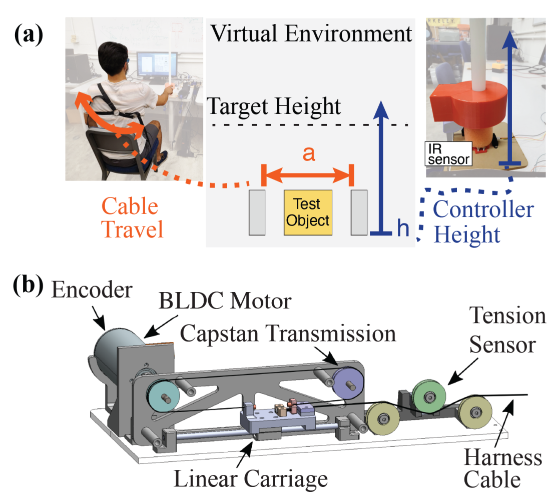

Fig. 2. Summary of key elements in body-powered prosthesis emulator test bed, adapted from [9]. (a) The simulated grasping environment as visualized in the environmental GUI with a test object (yellow) and opposed gripper (grey) and its associated user inputs. (b) Cross-sectional view of the desktop haptic interface with key elements labeled.

TABLE II
SIMULATED TEST OBJECT PROPERTIES

	Object A	Object B	Object C
Width (mm)	50	50	60
Mass (kg)	1	1.5	3
Stiffness (N/mm)	1	5	5
Friction Coeff.	0.7	0.7	0.7
Req. Force (N)	7.0	10.5	21.0
Description	Soft, Light	Medium	Large, Heavy

the simulated environment, while lifting the height controller raises and lowers the two sides of the gripper. The selected transmission condition determines both the rate of gripper movement relative to a given cable travel input and the level of force to display back to the user. A simple one-dimensional dynamic model governs the motion of the test object using calculations of the applied grasp forces based on the object's defined properties, such as mass, size, stiffness, and coefficient of friction.

The haptic interface, shown in Fig. 2(b), presents feedback forces to the user using a brushless DC (BLDC) motor (Maxon, EC-max 40). An encoder (Maxon, HEDL 5540) fixed to the motor's shaft measures travel of the harness cable through the capstan transmission and carriage system to constrain the cable to a single degree of freedom. An inline tension sensor drives an incremental PI controller to regulate the force delivered to the user. The target force is determined by the applied grasp force in the virtual environment and the current transmission condition being simulated.

B. Object characteristics

To contrast the different transmission conditions, we present users with distinct objects to grasp during the experiment, with varying object properties described in Table II. Object A represents a soft and light, but still relatively large, object analogous to a rolled-up towel where we expect users to have difficulty when operating a high transmission ratio device and succeed with a low transmission ratio one. Object C represents a heavy and stiff object which requires substantial grasp force to lift, analogous to a brick. Opposite to Object A, we expect a higher rate of grasp failures for low transmission ratio systems and higher rate of success with high transmission ratio systems. Object B represents a moderately sized and weighted object, which we do not expect to bias any of the constant transmission conditions.

C. Transmission modes

We base the simulated variable transmission used in this study off of the displacement CVT design found in the work by Matsushita et al. (2009) [14], with our benchtop prototype pictured in 3(a). This particular transmission is proposed for applications in robotic hands and selected for study due to its modeling simplicity and easy tunability.

Unlike prior art, we estimate the normal force N which actuates the transmission, rather than approximating this value with the cable tension force T. To do so, we approximate the transmission as a frictionless, equiangular polygon of n sides with contact occurring between the control cable and transmission at the vertices. We project the cable tension forces, applied along the polygon edges, onto the radial direction to estimate the normal force as

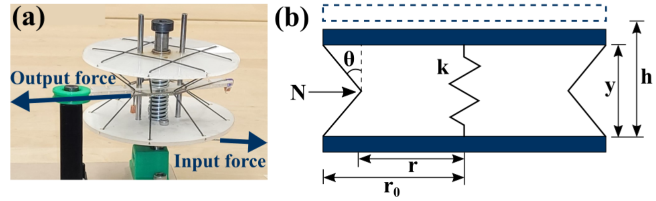

Fig. 3. (a) The initial CVT prototype on its benchtop setup. The transmission consists of two plates separated by a spring which dictates its force sensitivity. (b) Diagram of the displacement CVT with key variables labeled. Normal forces N applied by the control cable cause the functional radius of the transmission r to decrease and the transmission ratio to vary.

$$N(T) = 2T\cos\left(\frac{\pi}{2} - \frac{\pi}{n}\right) \tag{2}$$

By setting the tension force to a given value and using the model illustrated in 3(b), we solve for the string angle θ which satisfies the force balance equation

$$\theta\left(T\right) \Longrightarrow T = \frac{k\left(y_0 - h\cos\theta\right)\tan\theta}{n\cos\left(\frac{\pi}{2} - \frac{\pi}{n}\right)} \tag{3}$$

where k is the spring stiffness, y_0 is the standing height of the spring, and h is the initial height of the spring. We then find the functional radius of the transmission using

$$r\left(T\right) = r_0 - \frac{1}{2}h\sin\left(\theta\left(T\right)\right) \tag{4}$$

where r_0 is the initial transmission radius. We finally calculate the transmission ratio as a function of cable tension force input by dividing the constant input pulley radius r_c by the functional variable pulley radius $r\left(T\right)$.

$$R\left(T\right) = \frac{r_c}{r\left(T\right)} \tag{5}$$

For variable transmissions, we choose two systems to analyze, one representing a system with a high sensitivity to input force and the other a low sensitivity to input force. To evaluate the performance of these variable transmissions, we select a range of constant transmission ratios for comparison. A low transmission ratio system ($R = 0.5$) represents a device which optimizes output travel, while a high transmission ratio system ($R = 2.0$) represents a device which prioritizes output force. We also include a moderate transmission ratio system ($R = 1.0$) to benchmark performance between the two extremes.

The characteristic curves for these selected transmissions, in terms of input and output forces and travels, are reported in Fig. 4 and illustrate the benefits outlined in Sec. I. Fig. 4(a) shows how the transmission ratio of the variable transmissions increases continuously from 0.4 at no load to 1.1 (low sensitivity) and 1.6 (high sensitivity) at high loads. For an input force of 60 N, a conservative estimate of normative maximum shoulder strength [11], this results in amplified output forces of more than double (low sensitivity)

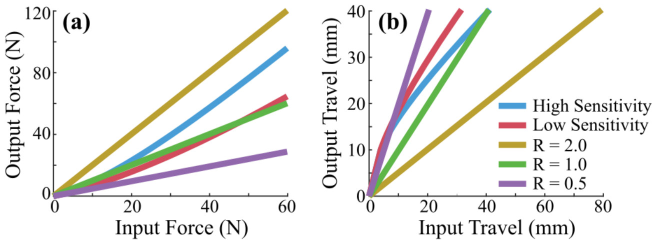

Fig. 4. (a) Predicted force outputs versus input forces for two selected variable transmissions and three constant ratio transmissions with slope denoting transmission ratio. (b) Predicted output travel versus input travel for two selected variable transmission and three constant ratio transmissions in a hypothetical grasping scenario. The width of the demonstrative object is such that contact occurs after 10 mm of output travel and a contact stiffness of 5 N/mm dictates estimated grasp forces and resulting transmission ratios.

and more than triple (high sensitivity) than what is achieved with the $R = 0.5$ transmission. Fig. 4(b) illustrates the limited output travel achieved by high transmission ratio systems even near the limits of nominal shoulder mobility with 80 mm of input travel. This plot shows the reduced travel demands of both variable transmissions. The variable transmissions require the least input travel before contacting the object and require comparable or less input travel than the moderate transmission ratio system, even when fully grasped.

D. Experimental procedure

Participants perform a grasp and lift task in a similar design to prior grasp force studies on normative grasp function [16]. For each trial, participants are instructed to grasp and lift a virtual test object displayed in the experimental GUI up to a minimum height of 15 cm. They are directed to hold the object at or above this target height for at least 5 seconds before releasing the object and returning the gripper to its initial lowered state, constituting the end of one trial. The GUI provides visual cues for each portion of the trial. From each trial, we estimate a number of performance metrics, including mean grasp and cable forces while holding the test object as well as accidental drop rate. We define an accidental drop as occurring anytime the test object is released prior to the end of a five second hold above the target height. Participants are told that speed does not factor into performance metrics, only applied forces. A video showing demonstrative trials for all control modes is included in supplemental media.

Each participant completes five sets of ten trials, each set under a different transmission condition: either one of three constant transmission ratios ($R = 0.5$, 1.0, and 2.0) or one of two different variable transmissions. The presentation order of each transmission condition is pseudo-randomized, and participants are not made aware of current conditions at any point during the experiment. This sequence is repeated for each of the three objects described in Table II.

Data represent a total of 4 non-amputee participants with normative upper limb function for this preliminary pilot study. Participants are affiliated with the Stuart research group and this project. All experimental procedures are approved by the University of California, Berkeley Institutional Review Board protocol #2019-05-12178.

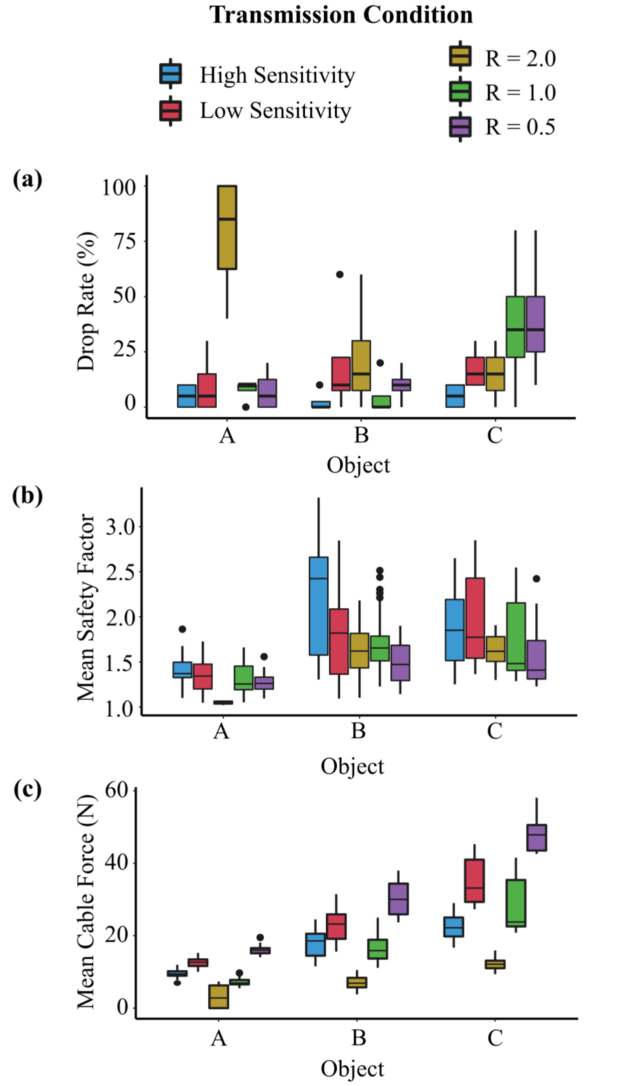

Fig. 5. Boxplot summary of data on grasp performance metrics: (a) Distribution of accidental drop rates over 10 trials. (b) Distribution of mean applied grasp forces while holding the simulated test objects during successful trials. (c) Distribution of mean user cable forces while holding the simulated test objects during successful trials. Data represent across all participants at each transmission condition and with each test object. Box edges denote the first and third quartiles, the dividing line denotes the median, whisker lengths are limited to 1.5 times the IQR, and outliers beyond the maximum whisker length are marked as points.

III. Results

Due to the preliminary nature of the study and small sample size, we only report group medians and interquartile ranges (IQRs) due to the presence of outliers and without any claims of significance. This will be left for future work following a larger study. Results for Mean Grasp Safety Factor (5(b)) and Mean Cable Force (5(c)) represent data collected from successful grasp and lift trials.

A. Accidental drop rate

Participants experience difficulty grasping different test objects under different transmission conditions, as seen in Fig. 5(a). For Object A (soft), individuals drop the test object 85% of the time with the high transmission ratio system ($R = 2.0$) due to the large required excursions approaching or exceeding their ranges of motion. For Object C (heavy), individuals struggle instead with the lower constant transmission ratio systems of $R = 0.5$ and $R = 1.0$ and drop the object in 35% of trials in both cases, over double that of any other transmission condition. Trials with Object B do not show clear preference with drop rates ranging between 0% and 15% across conditions. Across all objects tested, participants exhibit low drop rates with both variable transmissions, never exceeding a median drop rate of 15%.

B. Grasp force

Fig. 5(b) shows that participants routinely apply higher grasp forces with variable transmissions compared to the constant conditions while holding the test objects, as measured by the grasp safety factor. We define the safety factor as equal to the applied grasp force normalized by the minimum force to lift a given test object. Even under the most favorable comparisons, participants using the low sensitivity variable transmission apply an average of 6.4%, 10.1%, and 9.6% higher grasp forces than the worst-performing constant condition, respectively for each object. Individuals also apply less consistent mean holding grasp forces, particularly for heavier objects B and C. With Object B, for example, the IQR for grasp safety factor using the high and low sensitivity variable transmissions are 1.1 and 0.72, respectively, while the IQR for constant ratio transmissions do not exceed 0.39.

C. Cable force

For each object, user input force increases with decreasing transmission ratio as designed, shown in Fig. 5(c), with the variable transmissions producing moderate forces in relation to the other three constant conditions. For example, with Object C, participants experience median cable forces of 12.1 N, 23.8 N, and 47.8 N for transmission ratios of $R = 2.0$, $R = 1.0$, and $R = 0.5$, respectively, and cable forces of 22.2 N and 33.2 N for high and low sensitivity variable transmissions. Cable forces for the variable transmissions also decrease relative to the constant conditions with increasing input force, as seen with the high sensitivity transmission initially requiring 36.4% more force than the $R = 1.0$ case for Object A but 6.8% less force for Object C. Between objects, the overall cable forces increase due to the increasing weight of each object and the larger grasp forces required for lift. These differences in force imply adaptation on the part of users to each condition, changing behavior along with both object and transmission conditions.

D. Shoulder motion

Participants exhibited visibly different movement patterns depending on the transmission condition. Fig. 6 shows cable excursion over time for a demonstrative individual when grasping Object B with all transmission modes. The individual moves their shoulder the furthest when using the highest constant transmission ratio condition ($R = 2.0$) with a mean maximum excursion of 89.3 mm. The moderate constant condition of $R = 1.0$ results in 51.9 mm of peak excursion. Conversely, the participant operating the high and low sensitivity variable transmissions and $R = 0.5$ constant transmission experiences smaller ranges of motion, at 23.6 mm, 21.0 mm, and 25.1 mm of cable travel, respectively. Anecdotally, participants verbally expressed a preference for lower shoulder excursion.

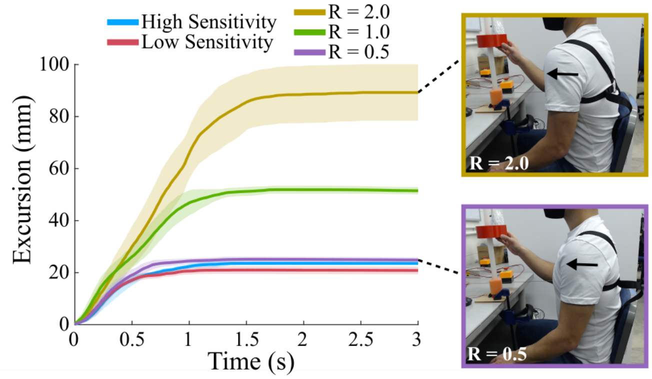

Fig. 6. Input cable excursion over time for each tested transmission condition during the lift and hold phases of Object B. Bold line and shaded regions represent the means and standard deviations, respectively, across 10 trials under each condition. Inset images show resulting posture at peak excursion under high constant transmission ratio conditions (top, gold) and low constant transmission ratio conditions (bottom, violet).

IV. Discussion

These results demonstrate that the high and low sensitivity variable transmissions allow users to achieve comparable force outputs with less shoulder movement. With these transmissions, users can grasp a range of objects varying in size, stiffness, and weight with a level of success not possible with any single constant transmission. Participants using the variable transmissions more effectively lift heavy objects, which pose challenges for the low constant ratio transmissions typical of body-powered prostheses that struggle with heavy objects [10]. They also more successfully lift soft objects, which present issues for the high ratio used in the discretely variable prosthetic device in [8]. However, these benefits appear to come with the cost of higher and less consistent grasp forces while operating the variable transmission systems and increases the risk of breaking fragile objects. It is possible that this cost could be an artifact of the test setup, such as confounds due to the order of transmissions presented or differences in learning rates between transmissions. Future work will investigate these potential effects through a longer study with additional participants.

The results also suggest that a combination of both user exertion and pose may contribute to increases in drop rate. As expected, high transmission ratio devices perform poorly for objects requiring small apertures, such as Object A, and low transmission ratio devices for objects requiring high forces, such as Object C. But the moderate transmission ratio system ($R = 1.0$) exhibited a similarly high drop rate as the high ratio system despite requiring comparable user input forces as the variable transmissions. While forces may be similar, the moderate ratio system also requires almost twice the cable excursion as the variable transmissions, leading to potentially awkward postures that may contribute to the observed increase in drop rate.

We can also compare our results to the outcomes in [9], in which excursion was kept constant across all force feedback modes. In prior work, grasp forces reduce by over half between minimum and maximum feedback force conditions. In the present work, the relationship between transmission ratios and applied grasp forces appears to be less pronounced, less than 15% for Objects B and C. The changing gripper position mappings relative to shoulder travel present in this work could attenuate the effect of force feedback for users. Future work will evaluate the role of proprioception in body-powered prosthesis control. In fact, studies performed on normative human grasping support the notion that proprioceptive signals play a primary role in dynamic grasping tasks [17].

V. Conclusion

Using a custom body-powered prosthesis emulator, we evaluate the function of a simulated variable transmission prosthesis (VTP), which represents a new study method for these types of prostheses. We demonstrate with a pilot study that a CVT, which changes its transmission ratio as it applies more force, provides better performance than constant transmissions, motivating further study and development. When compared to constant transmissions, we observed participants in a human subject experiment successfully grasped a wider range of test objects with a smaller and more desirable range of motion under variable transmission conditions. However, users also showed a tendency to apply larger grasp forces using variable transmissions, which suggests the presence of tradeoffs when considering the implementation of such systems into prostheses.

Further work will investigate the implementation of the CVT models used here into new VTP technologies which capture the benefits outlined in this work. The future development of variable transmission prototypes integrated with physical body-powered prostheses will evaluate the generalizability of these results to real-world environments. The application of variable transmissions to other contexts could also lead to the design of novel assistive devices, such as innovative upper-limb orthoses and exoskeletons.

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