Grasp Performance of a Soft Synergy-Based Prosthetic Hand: A Pilot Study

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***Abstract*— Current prosthetic hands are frequently rejected in part due to limited functionality and versatility. We assessed the feasibility of a novel prosthetic hand, the SoftHand Pro (SHP), whose design combines soft robotics and hand postural synergies. Able-bodied subjects (n = 23) tracked cursor motion by opening and closing the SHP and performed a grasp-lift-hold-release (GLHR) task with a sensorized cylindrical object of variable weight. The SHP control was driven by electromyographic (EMG) signals from two antagonistic muscles. Although the time to perform the GLHR task was longer for the SHP than native hand for the first few trials (10.2 ± 1.4 s and 2.13 ± 0.09 s, respectively), performance was much faster on subsequent trials (∼5 s). The SHP steady-state grip force was significantly modulated as a function of object weight ($p < 0.001$). For the native hand, however, peak and steady-state grip forces were modulated to a greater extent (+68% and +91%, respectively). These changes were mediated by the modulation of EMG amplitude and co-contraction. These data suggest that the SHP has a promise for prosthetic applications and point-to-design modifications that could improve the SHP.**

***Index Terms*— Myoelectric prosthesis, soft robotics, EMG.**

I. Introduction

CURRENTLY, upper limb amputation involves approximately 41,000 persons in the United States [1]. Despite the significant role that the hand plays in accomplishing a wide range of activities of daily living, prosthetic rejection rates are high: in a meta-analysis of prosthesis use and abandonment literature [2], Biddiss and Chau found the adult rejection rate for body-powered and electrically-powered prostheses to be 26% and 23%, respectively. Major reasons for rejection include heavy weight, lack of function and durability, discomfort, and poor cosmetic appearance. Furthermore, users often complain about the effort required to control upper extremity prostheses. In addition, current prostheses do not provide sensory feedback, which has been shown to affect the usage of prosthetic hands and sense of embodiment [3], [4]. Thus, research efforts have focused on improving prostheses appearance [2], [5], [6], function [2], [5]–[7], control [6], [8], comfort [2], [9], durability [5], and quality of feedback [2], [4].

To address these limitations, researchers at the University of Pisa and the Italian Institute of Technology converted a robotic hand, the SoftHand, into the SoftHand Pro (SHP) for prosthetic applications. The SHP design combines two design strategies, soft synergies [10] and under-actuation [11], to simplify the mechanics and control of robotic hands. The idea underlying soft synergies is to encode a movement pattern (here the first principal component extracted from hand postures) [12] into hardware design while allowing flexibility [13]. Under-actuation, or having fewer motors than degrees of freedom, enables an elegant implementation of the above design strategy, leading. The end result is an artificial hand with only one motor that can mold around objects in a physiological fashion while enabling stable grasps.

State-of-the-art myoelectric prosthetic hands consist of one degree of freedom hands with simple control, or multi-grasp hands that require more complex control inputs. The SHP's unique ability to conform to objects, combined with simple myoelectric control, make it an ideal starting point for a new prosthetic hand that addresses some of the unmet needs highlighted above. However, because the flexible nature of the SHP is a significant departure from typical prosthetic hand design, feasibility testing is needed to assess if this is truly an effective solution. Early studies have explored the feasibility of the SHP as a prosthetic terminal device [13], different myoelectric controllers [14], and possible integration with and utility of sensory feedback [4]. Despite these preliminary studies, systematic testing of SHP motion control, as well as its ability to perform grasping and manipulation, have not yet been performed. The present work addresses these issues on able-bodied individuals as an important step toward clinical

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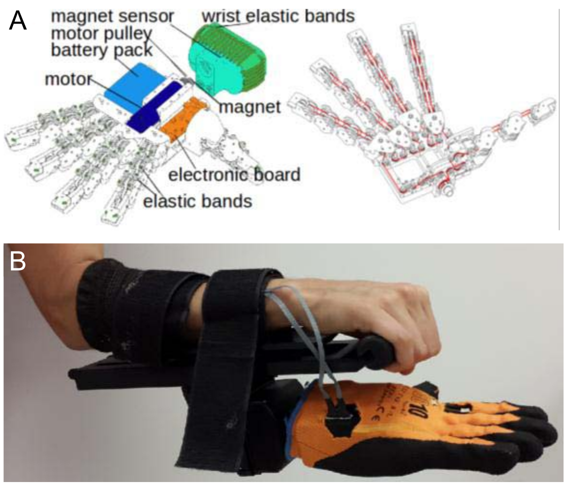

Fig. 1. SoftHand design and harness for testing able-bodied subjects.

testing with individuals with upper limb loss. Specifically, we sought to quantify subjects' ability to use the SHP to perform cursor tracking (mastery drills) and a simple object grasp-lift-and-hold (GLHR). Performance of the GLHR task was assessed as a function of practice and object weight. We asked subjects to perform the same task also with their native hand for comparison. A secondary and exploratory aim of the present study was to determine the efficacy of a set of mastery drills for helping subjects to perform the GLHR task the next day.

II. Methods

A. Subjects

Twenty-four self-identified right-handed subjects (age: 19-35 years, 13 males) participated in the study. One subject was excluded from analysis due to difficulties with myoelectric control of the SHP. Subjects had no history of neurological disorders nor experience with myoelectric control. Subjects gave informed written consent to participate in this Arizona State University IRB-approved study.

B. Apparatus

The SoftHand Pro (Design and Myoelectric Control): The SoftHand Pro (SHP) is a 19-joint under-actuated robotic hand (Fig. 1A). A single actuation cable runs through all of the joints and is driven by a single motor whose actuation closes the hand. The flexibility built into the digits allow them to mold around objects as they flex. Opening of the SHP is achieved by releasing tension in the cable and allowing elastomers to extend the joints of the digits [13].

The original design of the robotic version of the SHP has been modified for prosthetic applications by adding a myoelectric control interface [13] (Otto Bock electrodes, Germany). Surface electromyographic (EMG) signals are recorded from two antagonistic wrist muscles: a wrist flexor (flexor carpi radialis, FCR), and two wrist extensors (extensor carpi radialis and/or ulnaris, ECR and ECU, respectively). EMG from FCR and ECR was used to control closing and opening of the SHP, henceforth EMG1 and EMG2, respectively. The EMG signal is fed as a 10-bit value (scaled to the 5V EMG supply voltage)

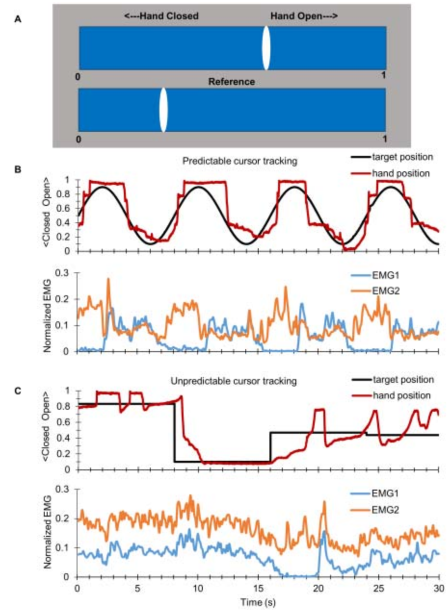

Fig. 2. Mastery exercises. A: Computer display of the feedback used for the mastery exercises (cursor tracking) with reference and subject cursor (bottom and top panel, respectively). B and C: Cursor and SHP motion (black and red traces, respectively) together with EMG signals from a representative trial for the predictive (0.125 Hz) and unpredictable cursor movement condition, respectively.

to a microcontroller. The SHP myoelectric controller is user-calibrated to optimize sensitivity. Hand movement is proportional to the difference of the two scaled EMG signals: when both are below threshold, the SHP holds position, whereas if EMG1 exceeds EMG2, the SHP closes proportionally to this difference, and vice versa. The velocity signal is a function of the difference between the amplitude of the two EMG signals, and integration of the velocity signal provides the reference position signal. Following contact with a rigid object, force exerted on the object increases if the reference position is more closed than is necessary to make contact. Note that for the present study, the SHP is mounted on a harness that can be worn on the forearm (Fig. 1B).

We used an active-marker motion tracking system (PhaseSpace) to record kinematics of SHP (1st and 2nd phalanges) and object. We used a 3D-printed sensorized cylindrical object (Fig. 3A,B) mounted over a horizontal base. We mounted each half to a 6D force/torque (F/T) sensors (Nano-25, ATI Industrial Automation), one on the thumb side and one on the finger side.

C. Experimental Protocols

1) Mastery Exercises: These exercises focus on controlling the speed and position of the SHP fingertips relative to the position of a moving cursor on a computer monitor. A cursor provided visual feedback of the closure state of the SHP (Fig. 2A). Subjects were instructed to follow the motion of a second, reference cursor by opening and closing the SHP and tracking it as accurately as possible. The reference cursor could move in a predictable or unpredictable fashion. During the predictable cursor tracking (Fig. 2B), the reference cursor moved back and forth in a sinusoidal fashion between 10% open and 90% of the SHP range of motion. For the unpredictable cursor tracking (Fig. 2C), the reference cursor moved from one position to the next in a random fashion but still within the same 10-90% closure range. For both conditions, subjects performed the exercise at four different frequencies that were presented across separate sets of trials: 0.125, 0.25, 0.5, and 0.8 Hz. Each trial lasted 30 s. To ensure the same number of movement cycles, the number of trials ranged from 20 at 0.125 Hz to 3 at 0.8 Hz.

2) Grasp, Lift, Hold, and Release Task: We designed an object grasp, lift, hold, release (GLHR) task to study how well the SHP users perform grasping and manipulation relative to their 'native' right hand. Performance was measured as (a) object motion, (b) grip force exerted by the SHP, and (c) EMG activity from forearm muscles responsible for opening and closing the SHP. The former two variables were also extracted from the native hand for comparison with the SHP.

After the computer delivered a 'go' signal, subjects lifted the object at self-selected pace and held the object for ~2 s. The experimenter verbally cued downward movement to replace the object on the table, and the trial ended after the subject released the object. The object kinematics focused on vertical motion of the cylinder and were combined with force data to define the following events and epochs illustrated in Fig. 3C: (a) contact: grip force exceeds the mean value of the unloaded grip force sensor output averaged across 0.3 s plus 2 SD of the mean; (b) end of the rising edge in the grip force: when grip force stops increasing; (c) object lift onset: vertical displacement of the object exceeds the baseline position of the object at rest averaged across 0.5 s plus 100 times the standard deviation of the mean (baseline data before movement); (d) end of lift: object reaches the target height of 5 cm; (e) replacement onset: object crosses the target height by moving towards the table; (f) beginning of the falling edge in grip force: grip force starts to decrease; (g) replacement offset: object vertical displacement returns to its baseline value measured before lift onset; and (h) release: grip force returns to baseline (zero force). Grip force stabilization epoch ("steady-state grip force", Fig. 3C) was defined as the epoch between events "b" and "f". For each trial, subjects were given 30 seconds to complete the GLHR task.

The GLHR trials were divided into three blocks. In Block 1 (trials 1-30), subjects grasped and lifted the sensorized object of 646 g with no added mass. In Block 2 (trials 31-60), the experimenter added a 400-g mass at the bottom of the object (total mass 1046 g). In Block 3 (trials 61-80), we asked subjects to use their native hand to perform the same GLHR task. The added mass remained in the sensorized object on trials 61-70, whereas it was removed for trials 71-80.

Subjects were randomly divided into four experimental groups (4-6 subjects each), with each given 10-15 minutes of familiarization practice with the SHP on day 1. The familiarization consisted of using the SHP to pick up objects of various shapes and sizes, e.g., a screwdriver, small and large rolls of tape, a plastic cup, a small 400 g mass, and a paper clip. Each training group underwent a different training regimen on day 1: Group 1 underwent the full set of mastery exercises; Group 2 underwent no mastery exercises but performed 45 minutes picking up objects of varying shapes and sizes (1 hour total); Group 3 received half doses of the mastery exercises and performed 15 minutes of additional familiarization practice (0.5 hour of each mastery and familiarization practice); and Group 4 received no additional training beyond the standard 10-15 minutes of familiarization. Groups 1-3 had similar practice durations on day 1 to rule out total time spent with the SHP as a confounding factor. All groups were tested on the GLHR task on day 2.

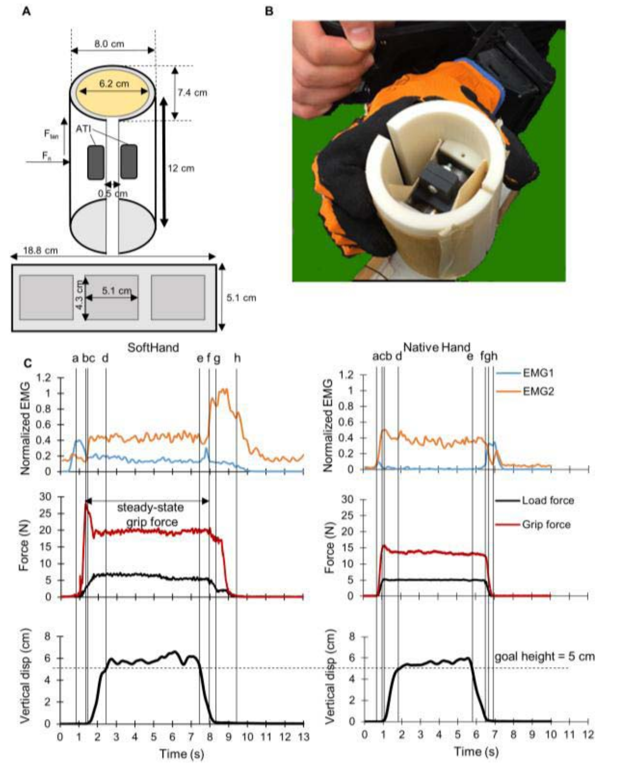

Fig. 3. Object and grasp task phases. A: Inverted T-shaped cylindrical force-sensing object used for the object GLHR task. Normal and tangential (vertical) forces applied by the SHP thumb and fingers are shown, Fn and Ftan, respectively. B: Top view of the SHP grasping the sensorized object. C: From top to bottom, the figure shows the time course of EMG activity from the EMG1 and EMG2, load and grip force exerted by the SHP on the sensorized object, and the vertical displacement of the object, respectively. SHP and native hand data are shown on the left and right column, respectively. Vertical lines indicate onset and offset of task epochs of interest.

D. Data Recording and Processing

Motion tracking data were sampled at ~233 Hz. Force, torque, and EMG data were acquired by 12 bit analog-to-digital converter boards (PCI-6225, National Instrument; sampling frequency: 1 kHz). Data acquisition was performed through LabVIEW (version 8.0, National Instrument).

E. Experimental Variables

1) Mastery Exercises: To quantify subjects' ability to control speed and position of the SHP through EMG, we computed the root mean square error (RMSE) between the reference and SHP cursor position from each trial (30-second recording).

2) GLHR Task (Temporal Variables):

a) Time to task completion: Sum of (1) time from the 'Go' cue to the end of lift, and (2) time from object replacement onset to release. An attempt to lift the object was defined as grip force rising above baseline and descending back to baseline. Failed trials were defined as instances when subjects could not complete the task within 30 s. Time-to-task completion of failed trials was counted as 30 s to facilitate analysis. Epochs that could not be analyzed during a failed trial (e.g., release duration; see below) were interpolated (for statistical purposes) from the trial preceding and following the failed trial. Percentage of failed trials was 3.5% (±0.9) across trials 1-5, and dropped to ∼0% after the first 10 trials.

b) Reach duration: Time between the 'go' cue and object contact on first successful grasping attempt. This epoch is relatively short because the subject begins the task with the SHP already near the object.

c) Contact-to-lift time: Time from contact to object lift onset ("a" to "c", Fig. 3C). This epoch reflects how long it takes to myoelectrically close the SHP.

d) Lift duration: Time from object lift onset to replacement onset ("c" to "d", Fig. 3C) reflecting the coordination of shoulder and elbow to accelerate the object upward.

e) Replacement duration: Time from replacement onset to replacement offset ("e" to "g", Fig. 3C). This epoch captures the coordination between shoulder and elbow motion.

f) Release duration: Time from replacement offset to release ("g" to "h", Fig. 3C). This variable reflects the time to myoelectrically open the SHP.

3) GLHR Task (Force Variables):

a) Peak grip force: This variable denotes the force that subjects exert prior or during the dynamic phase to prevent object slip and was computed as the peak grip force occurring at any time from contact to release offset.

b) Steady-state grip force: This variable represents the average grip force exerted from events "b" to "f" (Fig. 3C) to prevent object slip.

4) GLHR Task (EMG Variables): We analyzed the normalized magnitude of EMG signals from the wrist flexor and extensor muscles during four phases of the GLHR task: (1) force rise phase ("a" to "b", Fig. 3C), from contact to the onset of grip force stabilization; (2) holding phase ("b" to "f", Fig. 3C), time between onset and offset of grip force stabilization; (3) force falling phase ("f" to "h", Fig. 3C), time between offset of grip force stabilization to grip force baseline; and (4) post-task completion phase (after "h", Fig. 3C). All EMG analyses were performed on normalized values. During the force rise phase, EMG1 was expected to be larger than EMG2 and vice-versa during the opening phase. Subjects were given breaks (∼30 s) between trials to avoid fatigue. To obtain a measure of co-contraction magnitude, the two EMG signals were summated and averaged within each task phase and across all phases from the 'Go' cue to release. Co-contraction magnitude was expected to reflect potential changes in effort if subjects had progressively learned to exert similar levels of force with a decreasing (but better coordinated) effort.

F. Statistical Analysis

1) Mastery Exercises (Tracking Performance and EMG Co-Contraction Magnitude): Repeated measures ANOVA (rmANOVA) was performed on tracking RMSE and EMG co-contraction with within-subject factors: cursor frequency, cursor predictability, and trial. For each cursor frequency condition we averaged the RMSE within the 1st and 2nd half of the trials. We used linear regression analysis to quantify the relation between cursor tracking RMSE and (a) EMG co-contraction, and (b) task completion time during the GLHR task.

2) GLHR Task: Primary analysis focused on practice and object mass effects on temporal variables, grip force variables, and EMG co-contraction magnitude. Secondary analysis assessed whether performance of the GLHR task was sensitive to the training regimen undergone by each groups on day 1.

Primary analysis included rmANOVA with within-subject factors: number of trials (30 levels per object mass) and object mass (2 levels) on (a) the duration of individual task epochs and total time to task completion, (b) peak grip force and steady-state grip force, and (c) EMG co-contraction magnitude. For (c), we excluded two subjects because of missing EMG data. Bonferroni corrections were used for post-hoc comparisons. For secondary analysis, the between-subject factor of experimental group, i.e. the type of practice, was added to the above ANOVA.

3) Comparison of Functional Performance of SHP vs. Native Hand: Lastly, we compared the performance of the GLHR task by the SHP with the native hand on a subset of the above variables: time-to-task completion, peak grip force, and steady-state grip force. Note that we did not analyze EMG variables for the native hand as wrist muscles are not significantly modulated during reach-to-grasp (hand pre-shaping) or grip force production (see EMG signals from the native hand in Fig. 3C). For each subject we averaged time-to-task completion, peak grip force, and steady-state grip force across the last 10 trials of each block, and computed the ratio between SHP and native hand trials. We performed a paired t-test to assess differences in the SHP:native hand ratio between the two blocks. For all statistical analyses, we used $p < 0.05$.

III. Results

A. Performance of Mastery Exercises

1) RMSE: While there was no effect of cursor predictability on RMSE ($p > 0.05$), subject performance decreased for increasing cursor frequency ($F(3,15) = 28.17$, $p < 0.001$). Although not significant ($p = 0.065$), tracking performance trended towards improvement with practice (3.6% reduction in RMSE). The interaction between frequency and trial was significant ($F(3,15) = 10.49$, $p = 0.001$) and was due to a decreasing RMSE during practice with the highest frequency. The only significant decrease in RMSE between Trial half 1 and 2 was in the 0.8 Hz condition ($F(1,5) = 19.08$, $p < 0.05$).

2) EMG Co-Contraction: Subjects tended to co-contract their wrist flexors and extensors to a higher degree when tracking the cursor with predictable motion, and for higher movement frequencies (main effects of Predictability and Frequency: $F(1,4) = 12.59$ and $F(3,12) = 6.02$, respectively, both $p < 0.05$). However, practice yielded no changes in EMG

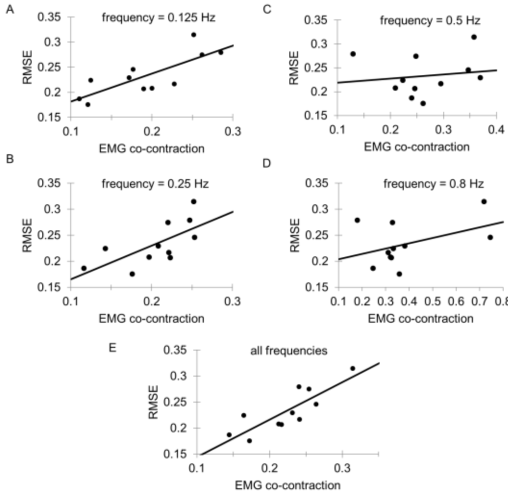

Fig. 4. Mastery exercises performance and EMG co-contraction. A-D: RMSE of cursor tracking performance is plotted against EMG co-contraction magnitude for each reference cursor frequency. Each data point is the mean data averaged across all trials per subject. E: RMSE is plotted against EMG co-contraction magnitude averaged across all trials and reference cursor frequencies averaged across each subject.

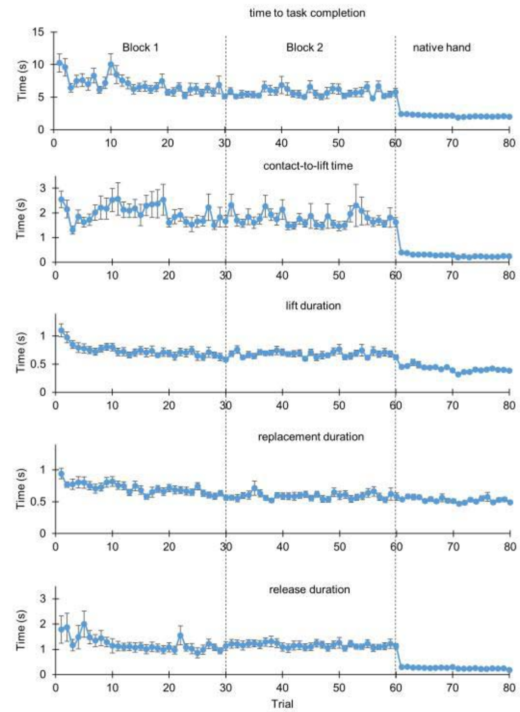

Fig. 5. Temporal variables as a function of practice. From top to bottom, data (average of all subjects ±SE) are time-to-task completion, the contact-to-lift time, lift duration, replacement duration, and release duration for the GLHR task plotted as a function of trial. Trials 1-60 were performed with the SHP, whereas trials 61-80 were performed with the native hand. Object mass was 667 g and 1067 g for trials 1-30 and 31-60, respectively.

co-contraction (no effect of trial). The Frequency × Predictability interaction was significant ($F(3,12) = 8.29$, $p < 0.05$) and was due to co-contraction increasing linearly for the predictable condition only. These differences were established by a significant frequency effect for the predictable condition only ($F(3,12) = 7.11$, $p < 0.05$). The positive linear relation between RMSE and EMG co-contraction for predictable cursor movement was statistically significant ($p < 0.05$).

3) RMSE and EMG Co-Contraction: To address whether a relation exists between RMSE and EMG co-contraction magnitude, we used data from Group 1 (5 subjects) and Group 3 (6 subjects) to increase the statistical power of the linear correlation analysis. The slopes of the linear fit were higher for lower cursor frequencies (0.56 and 0.65 for 0.125 and 0.25 Hz, respectively; 0.09 and 0.10 for 0.5 and 0.8 Hz, analysis performed on RMSE vs. EMG co-contraction data pooled across all cursor frequencies revealed the strongest linear correlation ($r = 0.76$, Fig. 4E).

These results indicate that subjects with greater ability to modulate EMG amplitude of the wrist flexor and extensor muscles could better control SHP motion by implementing a more reliable transition between opening and closing state. For lower cursor movement frequencies (Figs. 4A-B), the linear relation between RMSE and EMG co-contraction could be explained by the inter-subject variability in the ability to selectively contract one muscle over the other, respectively) (Fig. 4). The strength of the linear correlation between RMSE and muscle co-contraction was also greater for lower cursor frequencies, i.e., r-values = 0.72, 0.62, 0.13, and 0.40 for 0.125 Hz, 0.25 Hz, 0.5 Hz, and 0.8 Hz, respectively. The same

4) Temporal Variables: A major indicator of the subjects' performance during the GLHR task was the time to task completion and the extent to which this might have benefited from practice (Fig. 5). A few subjects required more than one attempt to perform the GLHR task on the first few trials. Specifically, subjects would fail to acquire a secure grip on the object during the first grasp attempt and would have to open the SHP before trying again. However, performance quickly improved after the first few trials, as indicated by time to task completion decreasing from 10.2 s (±1.4) for trial 1 to 5.1 s (±0.37) for trial 30 (Block 1), and remaining relatively constant during the second block (5.7 ±0.65 s; Block × Trial interaction; $F(29,638) = 1.94$, $p < 0.05$). This effect was confirmed by a significant effect of Trial in a one-way ANOVA only for Block 1 ($F(29,638) = 3.08$, $p < 0.05$).

All individual task epochs tended to improve in duration over the course of Block 1, though not all reached statistical significance. Contact-to-lift time decreased from 2.48 s (±0.33) for trial 1 to 1.66 s (±0.24) for trial 30 (Block 1). Lift duration decreased from 1.1 s (±0.12) to 0.58 s (±0.04). Replacement duration decreased from 0.94 s (±0.08) to 0.56 s (0.04). Release duration decreased from 2.2 s (±0.54) to 1.3 s (±0.16). Time before contact on the first successful grasping attempt decreased from 4.16 s (±1.27) to 1.23 s (±0.27).

Despite a trend towards improvement in Block 1, we found no effects of Trial or Block on the contact-to-lift time, likely due to the fact that the duration of this epoch was highly variable across trials and subjects. Specifically, subjects varied the amount of time they spent on the object after establishing contact, closing the SHP, and developing force to grasp the object before lifting it. The effect of Block was significant for both lift and replacement duration as these were generally longer for Block 1 than Block 2 ($F(1,22) = 4.86$ and $F(1,22) = 12.6$ respectively, both $p < 0.05$). Although lift duration

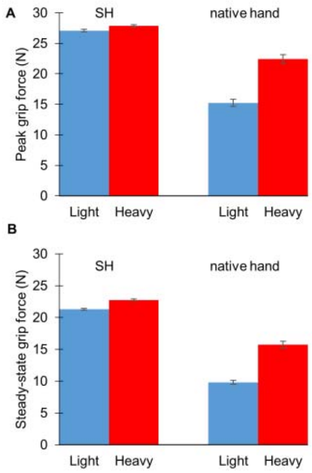

Fig. 6. GLHR task: Grip force. Peak grip force (A) and steady-state grip force (B) exerted by the SHP and native hand (left and right column, respectively) for the 'light' and 'heavy' object measured during the GLHR task. Vertical bars denote standard error of the mean.

decreased with practice in Block 1, it remained relatively constant in Block 2 (0.68 s ± 0.06; main effect of Trial; $F(29,638) = 2.89$, $p < 0.001$ and a Block $\times$ Trial interaction; $F(29,638) = 2.23$, $p < 0.001$). Lift duration decreased across trials within Block 1 only ($F(29,638) = 3.93$, $p < 0.001$).

Replacement duration did not show a significant effect of Trial ($p > 0.05$). Neither Block nor Trial significantly affected release duration ($p > 0.05$). Reach duration was significantly shorter for Block 2 than Block 1 ($F(1,9) = 6.4$, $p = 0.019$) but did not change significantly within each block. Thus, the decrease in time to task completion with practice was due to a reduced number of attempts necessary to grasp the object within trials and small improvements across all task epochs. The lack of statistical significance might be attributable to the large inter-subject variability in early trials of Block 1.

5) Grip Force Variables: Shortly after making contact with the sensorized object with the SHP, grip force reached a peak that roughly coincided with the lift-off ("c", Fig. 3C). During object lift, grip force decreased and reached steady-state value before the end of the lift ("d"). Grip force was maintained fairly constant throughout the static object hold phase ("d"-"e") and while the object was lowered on the table ("e"-"g"). Shortly after object replacement ("g"), grip force decreased while the digits extended and released the grip ("g"-"h"). The time course of the load force resembled the time course of grip force, even though load force was much lower than grip force.

For the SHP, we found no systematic changes in peak grip force across trials or between Block 1 and Block 2 (Fig. 6A; $p > 0.05$). The steady-state grip force for the SHP, however, was higher for the heavier object in Block 2 than Block 1 (Fig. 6B; $F(1,22) = 18.84$, $p < 0.001$), with no significant changes in steady-state grip force observed across trials.

6) EMG Variables: Modulation of EMG1 and EMG2 magnitude as a function of phase (opening-closing) differed depending on the block (Fig. 7A-B). Specifically, EMG1 in Block 2 was characterized by a greater difference between the holding and opening phase than Block 1 (Block $\times$ Phase

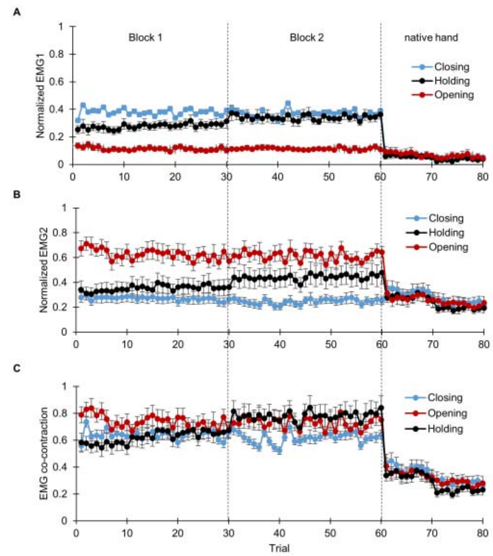

Fig. 7. GLHR task: EMG activity as a function of practice. The normalized magnitude of EMG1 and EMG2 (A and B, respectively) is plotted against trials. C: EMG co-contraction (sum of EMG1 and EMG2). For each plot, data is shown during SHP closing, opening, and holding phase. Data are means averaged across subjects. Vertical bars denote S.E.

interaction: $F(2,38) = 7.00$, $p < 0.01$). There was a main effect of Phase (Phase: $F(2.38) = 44.96$, $p < 0.001$) and a marginally significant effect of Block: $F(1,19) = 4.24$, $p = 0.054$). The differential phase effect between blocks was assessed using separate rmANOVAs for Block 1 and 2. During Block 1 and 2, EMG1 was largest in magnitude during the closing phase and smallest during the opening phase (main effect of Phase; $F(2,38) = 51.35$, $p < 0.001$ and $F(2,38) = 32.93$, $p < 0.001$, respectively). The results from EMG2 were similar to those of EMG1, but with an opposite pattern across phase and with a different effect of Block (Block $\times$ Phase interaction; $F(2,38) = 8.68$, $p = 0.001$). We found the same main effects from the rmANOVAs as described for EMG1 (Phase during Block 1 and 2; $F(2,38) = 37.49$ and $F(2,38) = 23.86$, respectively, both $p < 0.001$). As with EMG1, there was no change across trials.

EMG co-contraction across phases changed differently depending on the block (Block $\times$ Phase interaction: $F(2,38) = 11.97$, $p < 0.001$) (Fig. 7C). This interaction was caused by a modulation of co-contraction across phases only in Block 2 ($F2,38) = 3.54$, $p < 0.05$). In Block 2, EMG co-contraction was largest during the holding phase and smallest during the closing phase (Fig. 7C). For the closing phase, EMG co-contraction did not change across trials or blocks ($p > 0.05$).

B. Secondary Analysis: Effects of Training

Analyses of the preceding variables were independent of practice type. We analyzed the same variables with respect to the practice performed by each group the day before performing the GLHR task. These secondary analyses revealed no effects or interactions that would discriminate individuals from different groups on any of the variables, likely because there was so much individual variability in the SHP performance within group.

C. GLHR Task Performance for Native Hand Versus SHP Conditions

We asked subjects to perform the GLHR task also with their native hand to compare to the SHP, focusing on the total time to task completion, grip force, and steady-state grip force. Figure 3C (right column) shows EMG, force and object position data from one representative subject performing a GLHR trial with his native hand. Subjects were significantly faster in completing the GLHR task when using their native hand (compare right and left column data in Fig. 3C; $t = 2.02$, $p = 0.05$). The ratio of SHP to native hand time to task completion for both mass conditions combined was 2.82 ($\pm$ 0.21). Furthermore, peak grip force and steady-state grip force were significantly smaller when subjects used their native hand (Fig. 6A and B, respectively; $t = 2.97$, $p < 0.01$ and $t = 3.0864$, $p < 0.01$, respectively). The peak grip force and steady-state grip force SHP: native hand ratios across both mass conditions combined were 1.68 ± 0.13 and 1.91 ± 0.12, respectively.

IV. Discussion

The main goals of this pilot study were (1) to provide a detailed quantification of the ability of able-bodied individuals to perform motion control and manipulation tasks using a novel multi-degrees of freedom under-actuated robotic hand, the SoftHand Pro (SHP), and (2) use these results to infer its potential for hand prosthetic applications in individuals with upper limb loss. The main results of our study, together with preliminary work on individuals with upper limb loss (below), have provided significant information about strengths and weaknesses of the SHP design and controller. One of the key strengths of the SHP is that it is very easy to use and required minimum amount of practice. We interpret this finding as stemming from the combination of the soft-synergy design with simple myoelectric proportional control. Specifically, despite the lack of experience with the SHP and myoelectric control, subjects quickly learned to control the aperture of the hand, and grasping and manipulation of objects with different masses. This was accomplished by modulating EMG signals from two antagonistic forearm muscles. The main weakness revealed by our work to date is that grip force modulation to object mass with the SHP was significantly lower than when using the native hand. Although further work is needed to close the gap between the SHP and native hand performance, our findings demonstrate the potential for hand prosthetic applications of the SHP and will be instrumental in guiding important modifications in the SHP design.

A. Mastery Exercises and SHP Position Control

Mastery exercises provided no additional benefit relative to unstructured practice (practicing grasping with varied objects) or no practice. These results, however, might not be conclusive due to three factors. First, the statistical power of the parametric analysis is low as each group consisted of only four to six subjects. Second, it took all subjects only a few trials to improve performance of the GLHR task (see below), possibly creating a ceiling effect. Lastly, it is possible that skill transfer from mastery exercises to the GLHR task was not possible because of task differences, i.e., skilled control of the rate of switching between 'closing' and 'opening' EMG signals is only a subset of the skills needed for the GLHR task.

Despite these limitations, the mastery exercises provided important insight into SHP motion control. For example, the analysis of RMSE of SHP cursor tracking revealed that subjects can quickly reverse SHP motion direction regardless of whether the reference cursor motion is predictable or unpredictable. We also found the upper limit in motion frequency at which subjects encounter difficulties in quickly generating a differential EMG signal, thus leading to co-contraction. The identification of these performance metrics and tasks are important as they are potentially applicable to prosthetic training of individuals with upper limb loss.

B. SHP Performance of Grasping and Manipulation

Grasping and manipulation are an important component of many activities of daily living. Thus, prosthetic hands should enable users to confidently grasp and manipulate objects through aperture and grip force control. Hand aperture and timing control are important both to avoid collision with the object as the terminal device approaches the target and to release the grip when the manipulation is completed. Skilled control of grip force is required to correctly scale to object properties, such as mass, mass distribution, and friction [15]. Here we addressed two main questions: to what extent can GLHR performance improve with practice? and to what extent is SHP performance comparable to native hand performance?

1) Task Duration: An ideal terminal device should be easy and intuitive to use. A common approach to infer whether this criterion is fulfilled is to determine how long the user takes to perform a given task, e.g., Jebsen test [16]. Although time-to-task completion was more than twice as long when using the SHP than native hand, subjects were able to learn how to perform our task in less than 30 seconds for more than 98% of the time within the first 10 trials. The main cause for the few instances of task failure was subjects learning to adjust the closing speed of the SHP digits. Specifically, in the early trials the SHP tended to close too quickly as the subject positioned the hand around the object, thus forcing the subject to open, reposition, and close the SHP again to better grasp the object. This observation points to the critical importance of correct positioning of the SHP prior to closing the digits on the object. A limitation of the SHP design, which is shared by other prosthetic hands, is that subjects cannot use wrist muscles to pronate/supinate the SHP prior to object grasping. This is very different from how able-bodied individuals control grip axis orientation during reach and prior to object contact [17], [18]. Thus, a functionally important SHP design modification would consist of integrating the myoelectric control of the SHP opening/closing with control of an artificial wrist joint.

Among the task epochs of interest, contact-to-lift and release duration were much longer when using the SHP (Fig. 5). In contrast, the duration of object lift and replacement epochs were more similar for SHP and native hand. Contact-to-lift duration reflects a number of functionally important events.

In our task, subject had to verify that all SHP digits had made contact with the object. This could only be done through visual and auditory feedback, as the SHP lacks tactile feedback for contact detection. After object contact has been verified, wrist flexor EMG activity must increase to generate a grip force that is sufficient to establish a stable grasp in preparation for object lift. As the object is rigid, subjects might have maximized the rate at which EMG increased and generate very large forces. Regarding object lift-off, during the first few trials subjects had to re-grasp the object a few times, and in some instances this led to failed trials. A conservative strategy would be to exert a much larger force than required, a strategy that is not found in individuals using their native hand (Fig. 6A). Subjects might have chosen this strategy due to lack of tactile sensing as well as sense of effort based on feedforward commands to wrist muscles. Consistent with this interpretation is the finding that contact-to-lift time duration did not improve with practice within either block of trials. As release duration did not significantly improve with practice, either, subjects might have used a 'default' duration of changing the ratio of EMG1 to EMG2 to switch from 'closing' to 'opening' commands. Interestingly, both object lift and replacement benefited from practice. As these phases are mediated by shoulder and elbow muscles, this improvement in movement duration might reflect greater confidence with using the SHP and having verified the grip force required to avoid object re-grasp or slip in earlier trials.

2) Grip Force Control: Examination of peak and steady-state grip force exerted by the SHP during the GLHR task and comparison with the native hand can offer important insights into how users adapt to controlling the SHP. Peak grip force reflects feedforward control of the force necessary to establish a stable grasp and accelerate the object while preventing the hand from slipping. Peak grip force scales with object weight and depends on subjects' ability to form and retrieve sensorimotor memory of object properties formed across previous manipulations [19]. Steady-state grip force denotes grasp control quality, whereby subjects tend to use grip force that is slightly above that required to prevent object slip [20].

Because of lack of tactile feedback, the predominant source of feedback about object mass was proprioceptive feedback from arm muscles involved with lifting, holding, and replacing the object. This would account for grip force modulation to object mass learned through practice (Fig. 6B). However, lack of feedback was clearly a limitation in subjects' ability to predictively scale grip force to object weight (Fig. 6A) and, most importantly, in the weaker modulation of peak and steady-state force relative to the native hand (Fig. 6). A similar observation has also been made in patients affected by carpal tunnel syndrome who exhibit impaired tactile sensation and weaker modulation of grip force to object weight [21].

The crucial role of tactile feedback for force modulation to object weight might also partially explain why different types of practice and mastery exercises with the SHP did not lead to significant differences in subjects' ability to control grip force in the GLHR task. These findings on grip force variables point to the need of embedding contact force feedback to promote a force modulation to object properties that would more closely resemble the modulation found with the native hand.

C. Myoelectric SHP Control

The main challenge in designing a prosthetic hand with a high level of functionality and versatility is how to best reach a trade-off between mechanical complexity and intuitive control. Ideally, the prosthetic hand would have anthropomorphic features to increase both functionality and user acceptance. This, however, would require a complex controller to coordinate the action of multiple joints or digits, increasing the user's cognitive burden. The mechanical design of the SHP, based on soft robotics and postural synergies, is unique among other artificial hand prototypes [22] or commercially-available prosthetic hands [23], [24]. Specifically, the SHP design allows the user to control multiple degrees of freedom of the SHP through an intuitive myoelectric control algorithm using only two antagonistic muscles. Our results suggest that the combination of intelligent mechanical design and simple myoelectric control algorithm played a significant role in subjects to quick adaptation to the SHP.

The changes in EMG1 and EMG2 magnitude were expected based on the design of myoelectric control algorithm. Specifically, object grasping and holding were associated with larger EMG1 amplitude as this was responsible for SHP closing, whereas object replacement and release were characterized by larger EMG2 amplitude as this drove SHP opening (Fig. 7). However, analysis of EMG co-contraction, or sum of EMG1 and EMG2 amplitude, provided important insights. EMG co-contraction was modulated differently across opening-closing-holding phases but only for the heavier object where co-contraction was largest during the holding phase and smallest during the closing phase (Block 2, Fig. 7C). The larger co-contraction associated with the holding phase was driven by an increase in both EMG1 and EMG2 amplitude, and this resulted in the above-discussed small modulation of grip force to object weight. In contrast, the smaller co-contraction associated with the closing phase was mostly driven by a reduction in EMG2 amplitude in Block 2 relative to Block 1. These findings underscore subjects' ability to adapt the neural drive to the muscles responsible for controlling SHP motion and force with relatively little practice.

Additional Considerations: Even though we used only one object shape for the GLHR task, qualitative observations of subjects grasping several objects during the unstructured practice, as well as findings from preliminary studies [4], [13], [25], indicate that subjects could easily grasp, lift, and manipulate other objects with a variety of sizes and shapes and little practice. As all the joints of the SHP move until they encounter resistance (object surface), the SHP design allows the hand to conform to large objects (whole-hand grasp, such as for our cylindrical object; Fig. 2B), as well as grasp small objects thumb and index finger. Nevertheless, further work on a wider range of tasks and object shapes is needed to further quantify strengths and weaknesses of the SHP grasping capabilities. Nevertheless, preliminary results on individuals with upper limb loss (below) support the notion of SHP's feasibility for prosthetic applications.

D. Methodological Considerations and Preliminary Work on Transradial Amputees

The above-described results indicate that the SHP has great potential for prosthetic applications. However, several methodological considerations should be made about the present findings. An important point is that the present study was conducted on able-bodied individuals. Therefore, caution should be observed in extrapolating the present findings to individuals with upper limb loss. Specifically, the quality of EMG signal, thus control, of a myoelectric terminal device depends on several factors, including time since amputation, the degree of previous experience in operating myoelectrically-controlled prostheses, and age [5]. Furthermore, a direct comparison between the present findings and those that could be obtained in persons with upper limb loss is further limited by the fact that wearing a harness is not directly comparable to using the SHP through a socket. Specifically, our subjects wore the SHP harness through Velcro straps, whereas individuals with upper limb loss would wear the SHP through a custom-built socket to ensure a good fit with the residual limb.

Interestingly, preliminary observations suggest that persons with upper limb loss can use the SHP after minimal training with comparable proficiency as the myoelectric terminal device they have used for years [26] in many different tasks. Furthermore, while existing prosthesis users score reasonably well on various clinical scales with the SHP upon first exposure, they show noticeable improvement and mastery in roughly 1 full day of training [27]–[30]. These results show the SHP to be a potential alternative to current prosthetic hands.

Note also that a sensorized object was used to gain additional insight beyond that provided by analysis of temporal variables. There is extensive literature on sensorimotor control of grasping, and in particular on how grip force modulates to object mass, friction, and center of mass [15]. Here, we capitalized on this literature to extract experimental variables that could inform us about the SHP capabilities in performing a simple object grasp, lift, hold, and replace task. Through the present approach, we were able to characterize the extent to which subjects could modulate force to object weight, apply grasp performance metrics to quantify prosthetic hand performance, and guide future design modifications to the SHP. Nevertheless, we recognize that alternative or complementary approaches exist to measure the functionality/performance of terminal devices. In an ongoing study, we are combining the use of our grasp performance variables with commonly-used clinical tests (e.g., Activities Measure for Upper Limb Amputees [31], Jebsen Taylor test of hand function [16]) to provide a more comprehensive assessment of the SHP capabilities on patients with upper limb loss.[28]

V. Conclusions

The present study was motivated by the need to perform feasibility testing on how users learn to interact with the SoftHand Pro (SHP), a novel prosthetic hand. Importantly, the functional outcomes of the SHP result from two interrelated factors: (1) how the user adapts, on a trial-to-trial basis, to the terminal device's mechanical characteristics, and (2) the intrinsic features of the terminal device itself that impose constraints on how the SHP responds to myoelectric signals. The novel results of the present study indicate that able-bodied individuals with no previous experience in operating a myoelectric-controlled prosthetic device can quickly learn to use the myoelectric SHP to perform position-control as well as grasp and manipulation tasks. Preliminary findings on transradial amputees confirm these observations. The modulation of steady-state grip force to object mass and time-to-task completion were among the performance metrics that improved following a relatively short amount of practice. Despite this performance improvement, however, the SHP still underperformed relative to the native hand. Ongoing work on individuals with upper limb loss is aiming at identifying factors that can enable performance of a wide range of ADLs, including the addition of position and force feedback to the SHP.

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