Title

Grip Amplifier: Design of a Residual Force Control Strategy to Support Pinch Grip with a Minimalistic Hand Exoskeleton

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Grip Amplifier: A Residual Force Control Strategy to Support Pinch Grip with a Minimalistic Hand Exoskeleton

THESIS

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for the degree of

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by

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ABSTRACT OF THE THESIS

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By

Quentin Sanders

Master of Science in Mechanical & Aerospace Engineering

University of California, Irvine, 2018

Professor David Reinkensmeyer, Chair

Hand exoskeletons could potentially improve hand use after stroke, but are typically obtrusive, and lack intuitive control. Here we propose a grip force strategy suitable for a minimalistic hand exoskeleton based on three key concepts. First, people achieve substantial hand functionality when using only pinch grip. Second, people who have a stroke retain isometric force control ability. Third, force generation is highly correlated between fingers after a stroke. From these observations we developed a control strategy based on measuring the isometric flexion force produced by digits 3-5 against the palm to control the force of an exoskeleton assisting in pinch grip. We implemented this "residual force control" strategy (RFCS) using the FINGER exoskeleton with ten unimpaired participants. Participants performed five sets of five lifts with no exoskeleton, with the exoskeleton donned on but powered off, and with the RFCS using two amplification gains. When using the RFCS participants were asked to maximize the contribution of the robot to object force, and we displayed the percent robot contribution using a computer monitor after each set. Participants were able to use the RFCS to lift the object, significantly increasing the contribution of force by the robot as the sets progressed. However, the grip force

became larger and less dynamic compared to when participants were not wearing the exoskeleton. This suggests that unimpaired subjects could intuitively use this strategy to pick up an object and learn to amplify their grip force with practice. However, the strategy alters the normal grip force control strategy.

INTRODUCTION

Within the United States, there are over five million people who have suffered from a stroke, with over 700,000 people experiencing a new stroke each year, and globally an estimated 15 million [1]. Up to 85 % of stroke survivors experience hemiparesis, with 55% to 75% having limited upper-extremity function [2]. Hand impairments range widely from flaccid paralysis to complications with finger individuation representing a major challenge to quality of life, because the hands play a vital role in the performance of activities of daily living (ADLs).

Recently studies have shown that intensive movement practice can reduce hand impairment, giving back some functionality [3]–[7]. However, cost and accessibility greatly limit the amount of rehabilitation exercise delivered one-on-one to patients by therapists [8], [9]. To overcome the limitations of conventional therapy, robots have been suggested for use in rehabilitation. It has been shown that robotic repetitive movement training can be more effective than conventional hand therapy, especially for patients who have difficulty in performing unassisted repetitive movements [10]. These robotic systems can also be used to evaluate progress quantitatively, making the use of exoskeletons for assistive, and rehabilitative purposes particularly advantageous.

Many research groups have developed hand exoskeletons for both rehabilitation and assistance applications [10]. Although there have been many exoskeletons developed in previous years, many of these devices are not suitable for routine use in daily life. In 2008, a review of robot-assisted rehabilitation of hand function identified over 30 devices in existence, ranging from single DOF systems to 18 DOF systems [11]. However, only 25% of these devices had undergone any testing with stroke survivors, with many of the devices that were tested mainly being tabletop rehabilitation therapy devices. Further, the authors concluded that "A reason nearly 75% of the reported devices have not undergone any testing on the real users may be that these robots are too complex to be used by patients". A more recent survey of robotic devices for upper limb rehabilitation conducted in 2014 described over 120 devices [12]. Although it appears that there are many devices available, few focus on supporting basic ADLs at home, as only 30 of the 120 described devices were designed specifically for the hand as opposed to the arm.

To our knowledge only three hand exoskeletons for home use are available commercially. The SEM Glove [13] is an electrically-powered glove that senses force applied to an object then uses this force to amplify finger flexion forces via tendons running through the glove. The Daiya glove is a pneumatic glove that augments grip strength and is controlled via a switch on the side of the hand that inflates and deflates the glove. The SaeboFlex is a rigid orthosis that relies on springs to counterbalance the stiffness of the hand and assist with extension of the fingers and thumb after an object is grasped. But, even among these commercially available products there still exist several limitations. Most of the devices mentioned cover the finger pads of the hand preventing haptic input to the user, with the SEM glove being a partial exception as it leaves the index and little finger uncovered. Second, many of the devices require the user to have a substantial level of hand function limiting the pool of applicable users. For example, the Saeboflex requires the user to overcome the stiffness of the spring in order to grasp an object, and the SEM glove requires the user to already be able to make different hand grips. Lastly, most of these devices lack intuitive control, with most relying on switch-based control, meaning that the user must cognitively initiate another movement to cause movement of the hand. Thus, it remains unclear how a person with a stroke can achieve intuitive control of a hand exoskeleton. Finally, the devices mentioned above also tend to focus on facilitating power grasp. Perhaps this is because it seems at face value like the most common and most important thing for hands to do. Yet, assisting in power grasp requires a relatively large device that covers the hand, resulting in a bulky, and obtrusive design. This however, may not be necessary.

Pilot Experiments and their Implications

We performed preliminary experiments to study how using only one of two simpler grips, the thumb-index pinch grip, or the lateral pinch grip, affects hand function. In a first experiment, 11 participants without impairment performed the Box and Blocks test with their whole hand, then with the simpler grips. This test is a widely used assessment in stroke rehabilitation that measures the number of small blocks a person can lift and move over a divider in one minute [14]. We measured the percentage decrement in number of blocks moved in one minute with each simpler grip, compared to using the whole hand, unrestrained. Using only a single grip type allowed the participants to achieve 60-80% of normal function as measured by the Box and Blocks test. This data thus suggests that assisting only in one of these two simpler grips could result in restoration of substantial hand function.

We repeated a similar experiment protocol with a more comprehensive test, the Jebsen Hand Function Test, which measures the time required to complete seven different tasks that simulate activities of daily living[15]. Here, again, all tasks were still doable with minor increase in task completion time. The use of the thumb-index pinch grip exhibited the least increment in task completion time, but even using the key pinch grip, which requires only a very simple thumb movement, allowed participants to achieve a reasonable level of functional ability.

Consistent with this concept that simple grips can enable widespread function, people who use prosthetic hands often prefer the one degree of freedom, body-powered, terminal hook, which emulates a grip midway between thumb-index pinch and lateral pinch grip, and more dissimilar to a power wrap grasp. As explained by Biddiss and Chau, "Body-powered hooks [as compared to body-powered hands] are generally selected for functional value, durability, lower weight, and good visibility of objects being handled and, overall, are more acceptable to users"[16], [17]. <u>These concepts give way to the first key concept of this project: that by developing an exoskeleton that focuses on supporting a simpler grip, one may be able to achieve a substantial amount of hand function.</u>

Further experiments conducted in our lab offer insight as to how this minimalistic exoskeleton could be controlled. Our lab, and others have shown that people with stroke can accurately modulate flexion forces with their fingers, if the fingers remain isometric [18]. In a recent experiment conducted in our lab we asked 17 people with a stroke to participate in a grip force tracking game. Participants squeezed a force transducer with a power grip to move a cursor into a target at different force levels, defined relative to their maximum voluntary contraction (MVC), with the target window width set to ~1.5-3% of MVC [19]. Even participants with Box and Blocks scores as low as 3 were able to acquire the target with the time to acquire the target elevated at most by about a second. However, as soon as finger movement is allowed, force production drops significant, particularly during finger extension [20].<u>This force control data establishes a second key concept essential to this project: many people with stroke have a relatively well preserved but "masked" ability to modulate flexion forces with the fingers. Thus, isometric flexion force is potentially a high-fidelity force control signal source still available after stroke, but it must be translated into finger movement.</u>

Additionally, we have recently shown that the index and middle finger generate highly correlated forces, even when participants with a severe stroke were asked to generate forces with the fingers independently, consistent with the concept of abnormal synergy [21]. <u>This suggests a third key concept for this project: that it would be intuitive (or even automatic) for people with stroke to use the force generated by one finger to amplify the force of another finger.</u>

Based on these observations, we propose pilot testing a residual force control (RFC) strategy to support pinch grip with a minimalistic exoskeleton. Specifically, we suggest measuring the isometric flexion force produced by digits 3-5 against the palm to control an exoskeleton assisting in pinch grip. Further, in this pilot testing of the RFC strategy we investigate if unimpaired subjects can learn to use the RFC strategy given visual feedback and observe how the RFC strategy affects grip force.

METHODS

PARTICIPANTS

Ten unimpaired, right handed participants took part in the study (8 male; 2 female). All participants provided written informed consent, and the study was approved by the Institutional Review Board of UC Irvine. All participants were considered healthy and were within the 20-30 age bracket. Study inclusion for participants was naivety to the experiment and lack of hand impairment.

EXPERIMENTAL SETUP

We tested the RFC strategy with the FINGER exoskeleton [22], [23] and a custom made pneumatic pressure sensor [24]. FINGER incorporates two eight-bar mechanisms with high-fidelity linear actuators to assist in a naturalistic gripping motion of digits 2 and 3. The FINGER exoskeleton is not minimalistic (i.e. it is large and bulky) but provided a high-fidelity testbed for force control of index finger movement. We modified FINGER by mounting it on a pivot beneath the forearm rest to allow subjects to flex and extend the elbow to rotate the forearm and FINGER in the vertical plane to lift an instrumented object. The instrumented object (Figure 1) was constructed from a 3D printed base (length: 2.5 in., width: 2.15 in., height: 2.15 in.) made from PLA plastic. The inside of the object was hollow to allow for placement of weights of different sizes and utilized a velcro strap on the outside of the base to securely fasten in the weights. The object was also outfitted with a 3-axis accelerometer (Grove – 3-Axis Analog Accelerometer ± 3g), and a single-axis mini s-bar load cell (Interface, SMA-200). Attached to the top of the base of the object were two acrylic handles that were epoxied to the base, and then attached to the mini s-bar load cell. A 500g weight was used in the study, and the total mass of the instrumented object including the weight was 600g. We also made a pneumatic force sensor (Figure 1). It is a soft air bladder constructed from a low durometer silicone (Eco flex 00-30) and connected to an electrical pressure sensor (Honeywell HASCDANN015PGAA5).

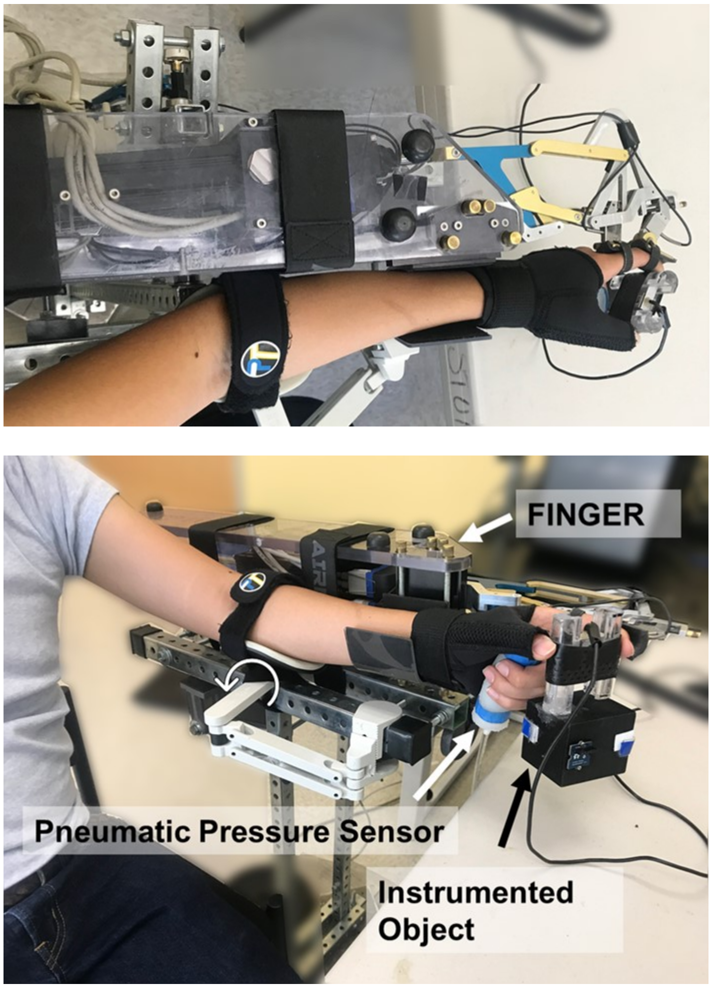

Figure 1. Experimental Setup up. FINGER exoskeleton mounted on the custom-built arm support which enabled flexion and extension of the elbow, allowing subjects to lift instrumented object in a vertical plane off the table.

CONTROL ARCHITECTURE

The controller used in this study is implemented in MATLAB xPC Target with a sampling frequency of 1000 Hz. A National Instruments 6221 DAQ card (16-Bits, 250kS/s) was used to acquire voltage signals from the accelerometers, load cell, and pressure sensor. For the RFC strategy, when digits 3-5 pressed the pressure sensor (creating signal F_{palm}) the exoskeleton provided an assistive force (F_{exo}) to the index finger which we measured from load cells embedded in the FINGER exoskeleton (Fig. 1). The RFC control law was:

$$F_{actuator} = K_{amp}F_{palm} \qquad (1)$$

Where $F_{actuator}$ is the force applied by the FINGER linear actuator to the 8-bar mechanism attached at the end of the actuator. The relationship between $F_{actuator}$ and F_{exo} depends on the kinematics and friction properties of the 8-bar mechanism (see next section). Two gains were selected for the study. The low gain was selected by experimentally identifying the relationship between $F_{actuator}$ and F_{exo} , then choosing the gain such that $F_{exo} = F_{palm}$. The high gain was selected such that $F_{exo} = 2*F_{palm}$. The total force applied to the object was:

$$F_{object} = F_{exo} + F_{index} \qquad (2)$$

Where F_{index} was the force produced by the index finger. In this experiment we focused on actuating only the index finger and used a thumb splint to hold the thumb in a gripping posture.

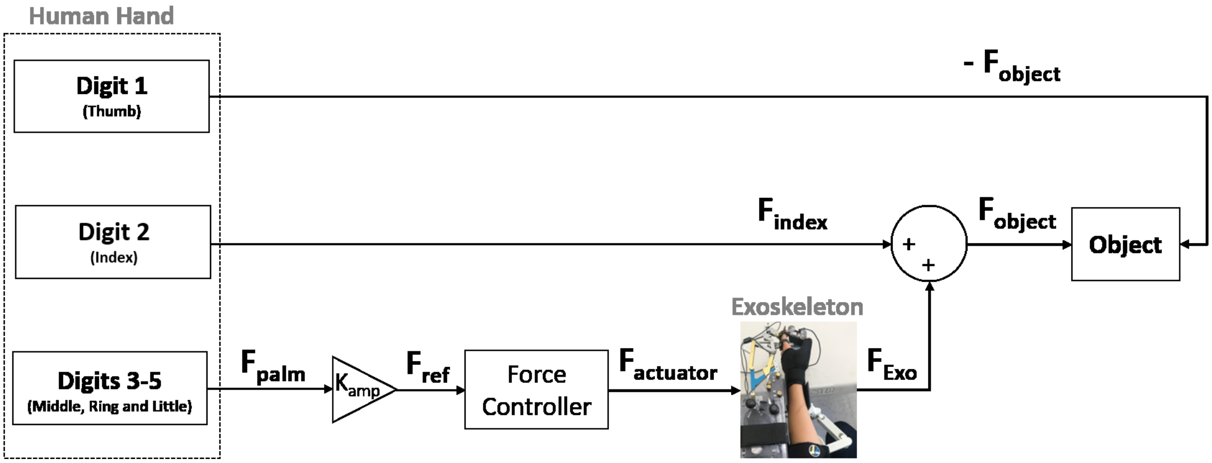

Figure 2: Control Architecture. When digits 3-5 pressed against the pneumatic pressure sensor the signal F_{palm} was created. This signal was amplified by a gain and fed into a force controller (F_{ref}). A force was then applied to the linear actuators causing movement of the 8-bar mechanisms attached to the end of the linear actuator. This in turn caused the human finger to move in the predefined curling pattern. The force exerted against the human finger by the exoskeleton (F_{Exo}) was then measured by a load cell embedded in the FINGER exoskeleton.

FRICITION COMPENSATION

The force applied to the finger F_{exo} differed from $F_{actuator}$ because of the frictional forces that arose due to static friction present in the linkages (Figure 3).

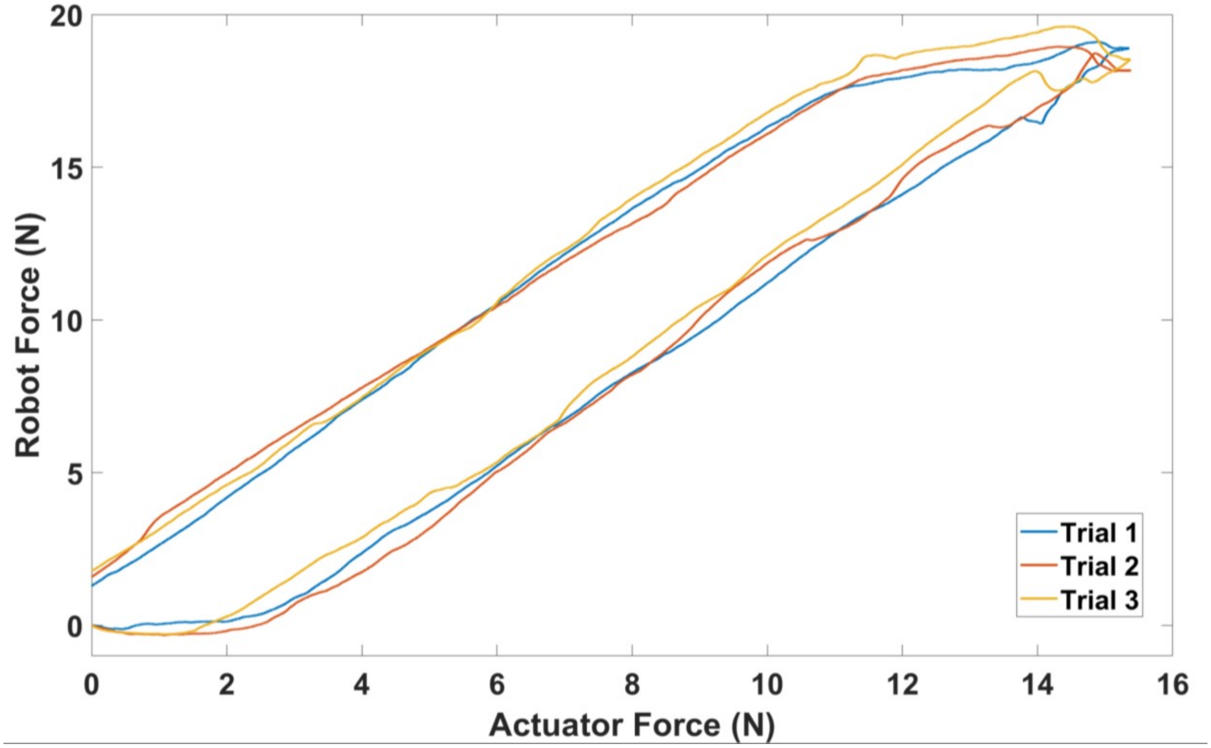

Figure 3. The relationship between actuator force, and the force measured by the loadcells in the FINGER exoskeleton is shown above. The measurement was taken 3 different times. Each time there was a large hysteresis due to the static friction present in the linkages of the FINGER exoskeleton. Conditions during each test were the same.

To account for this, we generated a table with the recorded values of $F_{actuator}$ and the corresponding F_{exo} values as we ran a ramp current through the FINGER exoskeleton. Note that this was done with the hand placed in the exoskeleton. A non-linear regression was performed on the data obtained from this process, where the regression function obtained was:

$$\widehat{F_{exo}} = -9.5e^{-7} * F_{Actuator}{}^{6} + 5.1e^{-5} * F_{Actuator}{}^{5} + -.00097 * F_{Actuator}{}^{4} + .007 * F_{Actuator}{}^{3} + .01 * F_{Actuator}{}^{2} + .80 * F_{Actuator} + -.65 \qquad (3)$$

was used to estimate robot force. Here x = $F_{actuator}$, i.e. the force applied by the linear actuator. Note that in this paper F_{exo} is referring to the estimated robot force $\widehat{F_{exo}}$ obtained from this equation.

EXPERIMENTAL PROTOCOL

Subjects were instructed to sit comfortably in front of a table, where the instrumented object was placed directly in front of them. Subjects were then instructed to grasp the instrumented object with digits 3-5 leaving the index finger and thumb free. Subjects performed a maximum voluntary contraction (MVC) test twice, in which subjects squeezed the instrumented object as hard as they could for 5 seconds. Afterwards the highest peak force of the two trials was taken as their MVC. After this task, subjects were then given instructions to use a pinch grip to grasp the same object. Subjects grasped the object and lifted the object approximately 2 inches above the ground for 10 seconds using only a pinch grip. This condition was denoted as "*Hands Only*". Subjects completed a total of 5 sets, with each set comprised of 5 lifts in this Hands Only condition. After completion of this task subjects were fastened into the FINGER robot. Note that the FINGER exoskeleton left the volar surface of the index finger free, so participants could sense tactile interactions with the object. Subjects then followed the same procedure, completing 5 total sets of 5 lifts. During this time the robot was powered off and did not provide any additional assistance to the subjects during the task. This condition is referred to as "*Hand in Exoskeleton, Powered off*" condition. After the baseline evaluation phase subjects were allocated into two different groups, with each group using the RFC strategy with both gains in a randomized order (Fig.4). Session order was randomized using a Williams Design Latin Square to minimize first order carryover effects. Subjects were also allowed to adjust the height of the seat to place themselves in the most comfortable position to perform the task. When the exoskeleton was on and participants were using the RFC strategy, participants were asked to perform the same task with the goal of minimizing F_{index} and maximizing $F_{exo,}$. Between each set was a "washout period" in which subjects performed 5 sets of 5 lifts with the goal of minimizing $\mathrm{F_{exo}}$ and maximizing $\mathrm{F_{index}}$. After each set (including the "wash out period"), participants received visual feedback on a computer screen which displayed the mean F_{exo} /F_{object} as well as the mean F_{index} /F_{object} over the previous 5 lifts after each set (Fig.5). We provided this feedback to determine if the participants could improve their ability to use the exoskeleton over time. Upon completion of the experiment subjects were also given a short survey asking them about their experience during the experiment.

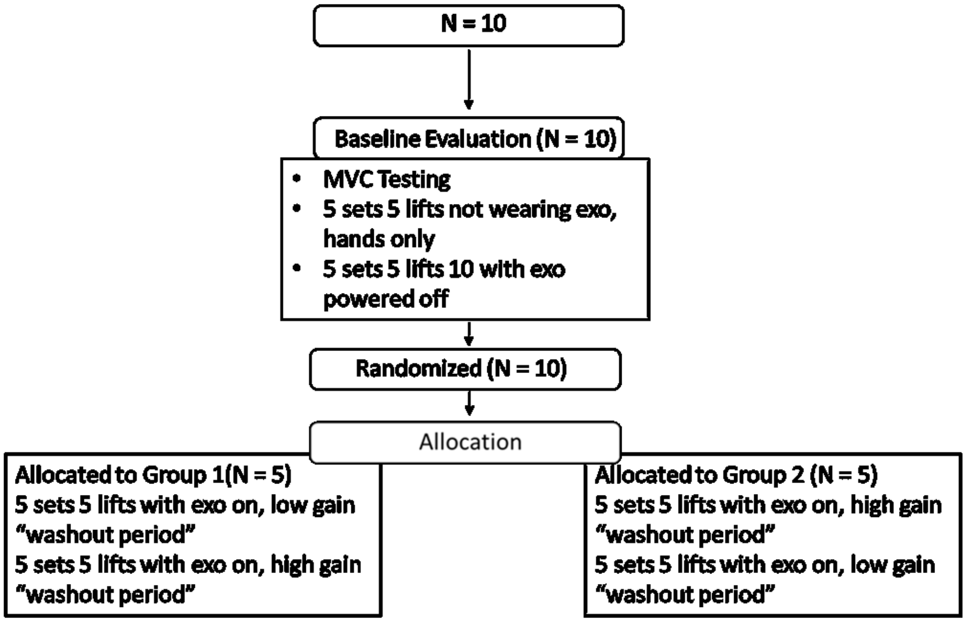

Figure 4. Flow chart of experiment. Subjects participated in the baseline evaluation phase where they performed the MVC Test, as well as performed the pinch grip lift hold task in the "hands only" condition, the "with Exo powered off" condition. Afterwards they were randomized and then performed the task using the RFC strategy with both gains. With "washout" periods between each set. Session Order was randomized, and subjects were allocated to each group.

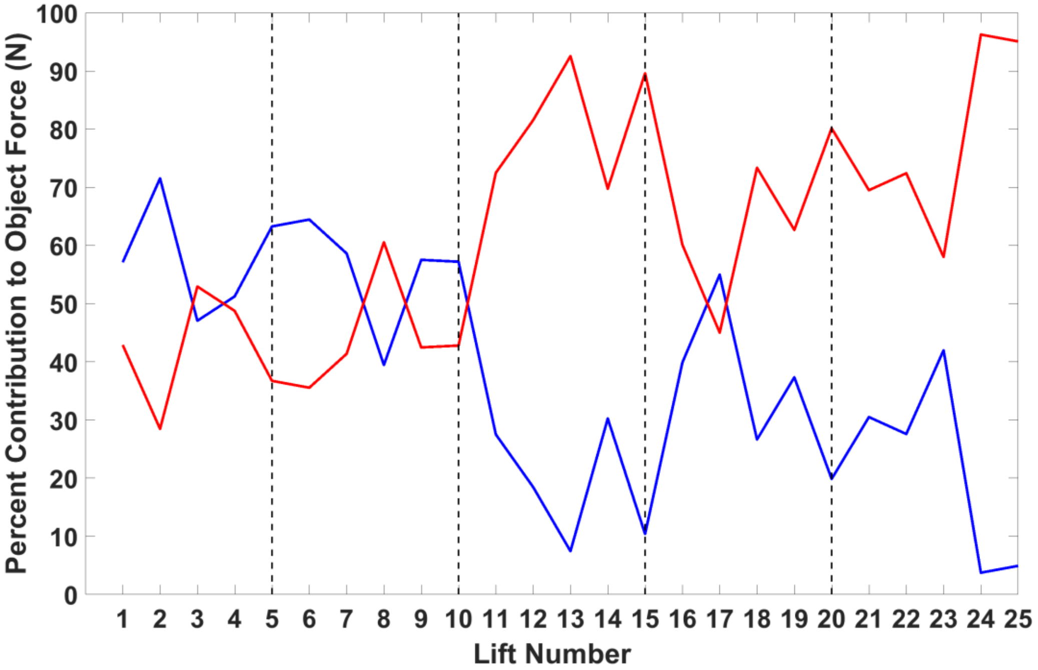

Figure 5. Example data from one subject across all five sets. After each set subjects would see the red line which indicated the percent contribution to the object force by the robot, and their own contribution to the object force (blue line). Upon the completion of a set which consisted of 5 lifts, a black dashed line as shown in the figure above was displayed to separate the current set from the previous set.

DATA ANALYSIS

OUTCOME MEASUREMENTS

In this study the primary outcome measures were the change in robot contribution to the grip force across all five sets ($\Delta\ F_{exo}/F_{object,}$), change in palm force across all five sets (ΔF_{palm}), change in index force across all five sets ($\Delta\ F_{index}$), and the change in the force measured by the instrumented object across all five sets in each of the different conditions (ΔF_{object}).

DATA PROCESSING

Raw data was exported for offline analysis in MATLAB, Using MATLAB Statistical Toolbox. A low pass Butterworth filter of 3 HZ was applied to the grip force, palm force, and robot force to reduce noise in the signals.

STATISTICS

In MATLAB, Lilliefors test for normality was conducted to determine whether the data followed a normal distribution. In SPSS a Two-way Repeated Measures ANOVA was conducted using Bonferroni correction method between $\Delta\ F_{exo}/F_{object}$ to determine if there was a learning effect (i.e F_{exo}/F_{object} Increased across sets), and if there was a significant interaction between the gain used and the robot's contribution to the object force. A repeated measures ANOVA was also conducted on ΔF_{object} to determine if there was a significant change in object force during the different experimental conditions *("hands only", "with exo powered off", "with exo powered on low gain", "with exo powered on high gain"*).

Results

Comparison of average percent contribution to grip force by subjects and the robot

In this study subjects were separated into two different groups. Group 1 used the RFCS with the low gain first, followed by the high gain while group 2 used the gains in the opposite order. Figure 5A below shows the average percent contribution to the object force by both the subject and the robot when the RFCS was in use. For both groups there was a significant increase in the contribution to the object force by the robot (Low Gain, $p = .004$, High Gain, $p<.001$, Repeated Measures Anova) as the sets progressed.

Figure 6B. & 6C give another representation of this result. The temporal pattern of the index force, robot force, and object force for the low gain, and the high gain are shown. By the 5th set the average force exerted by the robot for the low gain and the high was approximately 11N and 10N respectively. The contribution from the index finger for both gains was approximately 2N. Thus, by the end of the study subjects were able to allow the robot to contribute more to the object force in comparison to the contribution from their own force. However, after the gains were switched there no longer appeared to be a clear learning effect, as there was no consistent pattern of an increase in robot contribution to the object force as the sets progressed. Additionally, there was a significant interaction between the effects of the gain used on the robot contribution to the object force ($p <.001$, Two-Way Repeated Measures Anova). Specifically, simple main effects analysis showed that subjects who were using the high gain were able to allow the robot to contribute more to the object force as compared to the low gain by the end of the study ($p < .004$).

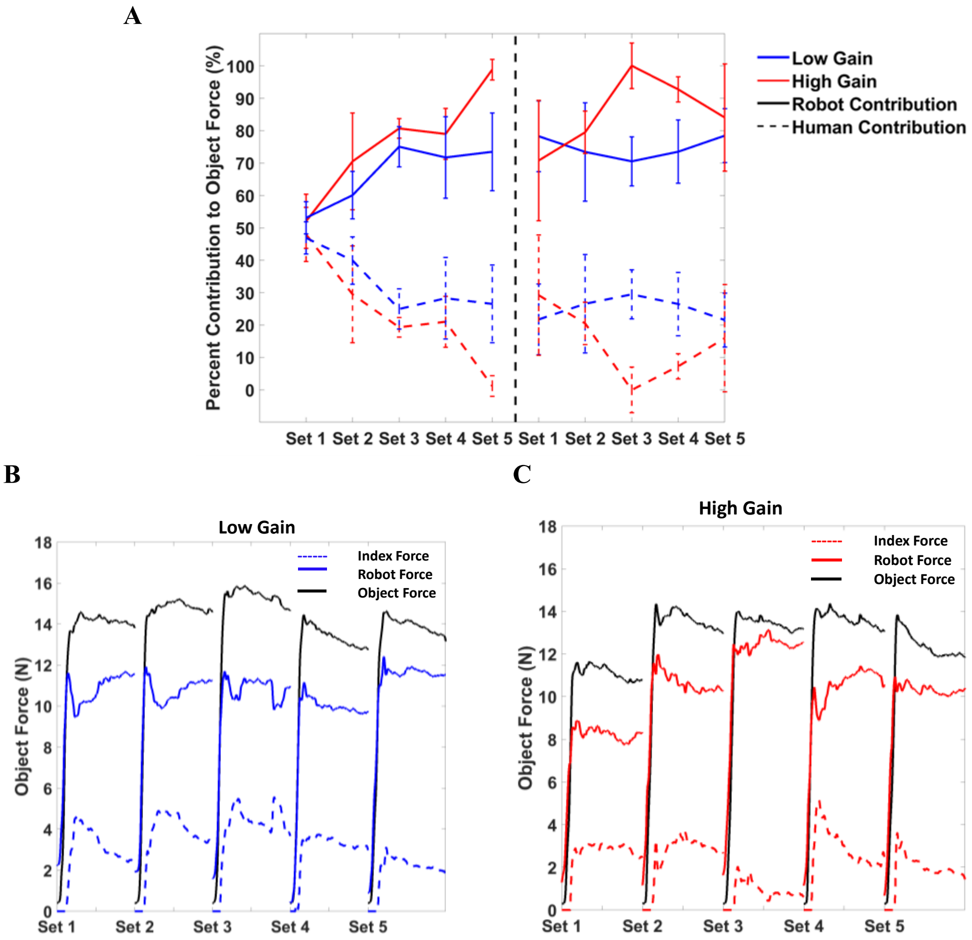

Figure 6 A. Percent contribution to total object force (as measured by the instrumented object) vs the set number for both gains. The black line in the center of the figure represents when the gains were switched. For the group that originally had the low gain first they switched to the high gain, and vice versa for the other group. B. Index force, robot force, and object force for the low gain for group 1 C. Index force, robot force, and object force for the high gain for group 2.

Temporal pattern of control and object forces during Residual Force Control Strategy compared to normal lifting

Figure 7 shows the average object force for the low gain exoskeleton powered on condition, high gain exoskeleton powered on condition, hand in exoskeleton powered off condition, and hands only not in exoskeleton condition. We observed a significant increase in the object force in each of the conditions as compared to the “Hands Only” condition (p <.001, Repeated Measures Anova). Additionally, in this study the object force during each lift decayed less slowly while using the RFCS in comparison to the “Hands Only” condition.

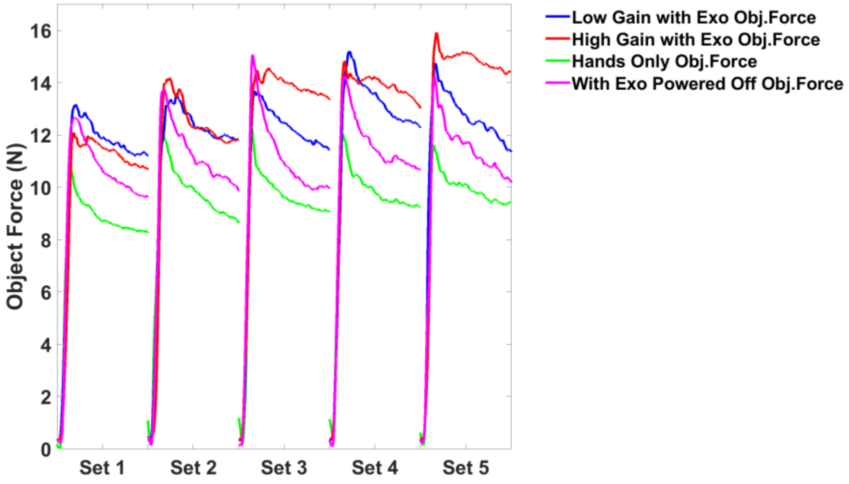

Figure 7. Object force vs set number for all conditions

Discussion

Implications of Residual Force Control Strategy on the Design and Control of Hand Exoskeletons

In the beginning of this paper we presented three key observations that drove the development of the residual force control strategy. Those three observations were: 1_unimpaired people can achieve a substantial level of clinical hand function with only a pinch grip; 2) people with severe hand impairment after stroke have a surprisingly well-preserved ability to control isometric finger flexion force; and 3) force generation is highly correlated between fingers after a stroke. These observations potentially could lead to a paradigm shift in the way that hand exoskeletons are controlled and designed. By assisting a simpler grip, one can potentially achieve a substantial amount of hand function while greatly reducing the bulk and complexity of the exoskeleton. Additionally, taking advantage of the hand's residual function, such as the masked ability to control isometric flexion force, may lead to more intuitive control. Movement control may be possible that involves only the impaired hand, instead of relying on non-intuitive, switch-based control schemes or the support of the opposite hand. Additionally, regarding the control strategy mentioned here, by taking advantage of this residual function it could potentially allow the hand exoskeleton to be used by a larger population of people. As mentioned in observation 2, even people with BBT scores as low as 3 were able to control their isometric finger flexion force. This would provide an advantage over the SEM Glove, which requires users to have a substantial amount of hand function to initiate various grasp types, or the SaeboFlex, which requires users to have enough hand function to overcome the stiffness of the spring to use the device.

Feasibility of Residual Force Control Strategy for a Hand Exoskeleton

We tested whether the residual force control strategy provided intuitive and dexterous control of pinch grip using a high-fidelity tabletop exoskeleton. We found that unimpaired participants were immediately able to use the residual force control strategy to pick up an object and learned to amplify their grip force with this strategy, reducing the force they needed to exert to lift the object with training. By the end of the experiment participants had learned to use the robot to produce a majority of the force (90% group 1, 70% group 2) to lift the object. Thus, the RFC strategy provided "grip amplification". Additionally, subjects were able to allow the robot to do more of the work when the amplification gain was higher.

Effects of Robotic Assistance on Object Force Pattern

Ideally, any control strategy for a hand exoskeleton would allow users to preserve their normal pattern of object force when lifting an object. Here, despite being able to intuitively use the RFC strategy, and improving their use of it over time, subjects altered their grip force trajectory when using the RFC strategy. Normally when an object is lifted the grip force rises until the maximum grip force is reached (typically coincident with maximum upward acceleration)[25], [26]. After the maximum grip force is reached the force decays in an exponential fashion as the motor system tries to reduce the amount of force it produces[26], [27]. In this study, however, subjects altered their grip force trajectory when using the RFC strategy. Specifically, they applied a slightly higher, less dynamic object force in a way that is consistent with becoming more conservative in preventing the object from dropping[26]. This may be because doing so decreased one of the variables we asked them to minimize: F_{index} / F_{object}. Another explanation of this could be due to slacking. When manipulating an object and error is not detected (i.e. object not slipping) the body systematically tries to reduce the amount of force its uses or "slacks". This slacking increases as you use more grip force and decreases at a slower rate when you are using less force. In the literature it states that the average MVC for healthy adult males when using pinch grip is about 75.62 N. For the "Hands only" condition the force was on average 9.67 N while for the low gain and high gain the human pinch grip force on average was 2.73 N and 4.56 N respectively. In the "Hands only" condition only about 10% of the recorded MVC was used while both gains were using less than 5% of MVC. As result, you would almost expect the force to decay at a slower rate when using the RFC due to slacking. However, we would like to perform follow-up experiments in order to validate if the rate at which the force decays is truly the result of slacking or if it is caused simply by participants trying to decrease one of the variables we asked them to minimize.

Limitations and Future Work

Our next aim is to perform a similar experiment with stroke survivors to validate if the RFC control strategy will indeed enable participants to perform functional tasks with their impaired hands. But, before doing this, several limitations need to be addressed.

Limitations of Current Visual Feedback

One limitation is the increase in object force magnitude we saw in this experiment, which made grasping less efficient with the RFC strategy. In future experiments, we would like to consider the effect of adding vibration as a form of force feedback or of changing the visual feedback to show subjects their force output, rather than just displaying their percent contribution to the object force, as we did in this experiment. This additional feedback could help prevent users from manipulating the current setup to increase F_{Exo}/ F_{object} and instead allow participants to learn to grasp more efficiently with the RFC strategy.

Hardware Limitations

There were limitations in the hardware we used to implement this experiment. There was static friction in the linkages of the exoskeleton, causing some uncertainty in the relationship between the commanded and applied force. Additionally, when subjects lifted the object, they applied normal forces to the FINGER linkages, bending them. The static friction also changed when there was a hand in the robot because the extra weight of the hand created additional loading on the joints.

The effect of this static friction altered the mapping between $F_{actuator}$ and F_{Exo}. As described above, we attempted to account for this mapping by performing a non-linear regression to obtain a relationship between $F_{Actuator}$ and F_{Exo}. The equation generated was used to calculate an estimated F_{Exo}. However, this equation did not consider that during lifting the loading on the joints was further increased, increasing the frictional forces. This caused the actual force applied to the finger to differ from the force that was measured by the load cells embedded in FINGER. Lastly, the force measured by the instrumented object could be diminished if the angle the finger made with the force transducer varied from being perpendicular. Future experiments should track this angle with a sensor.

Future Work

One logical progression of this work would be to improve the accuracy of the measurements. One approach to this would be to measure the static frictional forces required to move the mechanism from a rest position experimentally when a hand is in the FINGER exoskeleton. The average static frictional force could then be used to construct a feedforward friction compensator. Another approach is to develop better hardware. Use of the FINGER exoskeleton allowed us to quickly implement and test the RFC strategy, but FINGER is bulky and not designed to take lateral loading against the linkages.

Our ultimate goal is to develop a minimalistic hand exoskeleton for assisting in pinch grip. We have already started experimenting with soft pneumatic actuators and begun prototyping a minimalistic hand exoskeleton. The base of the hand exoskeleton is a soft fabric-based glove with thin metal splints placed inside the glove that hold the thumb in a slightly opposed position. For the actuation mechanism we chose to build upon the research findings of [28], [29]that present the idea of a robust, fiber-reinforced soft bending actuator capable of generating a significant amount of force. We chose to modify the fiber reinforced actuator by widening the cross section, covering both the index finger, and the middle finger. Already we have found that the actuator was able to generate 4 times as much force as compared to the original design of the actuator, while only increasing cross-sectional area by 1.7. This suggests that having an actuator for each individual finger may not be necessary. Instead, a single soft pneumatic actuator that covers two fingers could potentially be used, greatly reducing the bulk of the exoskeleton by covering less of the hand, while still generating enough force to support basic activities of daily living. This approach has the potentially of allowing us take advantage of the more comfortable compliant properties of soft materials as opposed to the rigid metal linkages of the FINGER exoskeleton materials, providing a less obtrusive device on which to implement the control strategy.

Conclusion

Participants were able to successfully learn to amplify their palm force and use the residual force control strategy to perform the task, although they increased the magnitude and altered the temporal dynamics of their object force. Currently, we are preparing to test the RFC strategy with people with a stroke. We hope to turn their isometric finger flexion control ability into functional hand movement, again by actuating index finger movement and holding the thumb in a gripping posture with a splint.

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