UNIVERSITY OF CALIFORNIA,
IRVINE

Hand Rehabilitation after Stroke: Understanding and Optimizing the Usage of Wearable Robotic Technologies

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Mechanical and Aerospace Engineering

by

Quentin Sanders

Dissertation Committee:
Professor David J. Reinkensmeyer, Chair
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2020

DEDICATION

To my biggest supporters; mom, dad, and my brother Phil

To Jichele, my wife and my best friend

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ACKNOWLEDGMENTS

Words cannot express that gratitude that I have towards Dr. David Reinkensmeyer. In the beginning of my graduate school career I wasn't very confident in my abilities as a researcher or as an engineer. But you looked past that, and were willing to give me an opportunity in your lab. You have helped me grow into the researcher that I am today. Thank you for all the encouragement that you offered, for challenging me to grow, for showing me grace when I made mistakes and needed it most, and finally providing a safe space to talk about not only research, but life as well. I will always look fondly on my time in graduate school because of the mentorship and guidance I received from you. I will surely miss our exciting conversations about research, and about the latest basketball news. To Dr. McCarthy thank you for the exciting conversations that we had about the development of my soft actuator. You provided valuable insight into the design of the actuator for my thesis, and have fostered in me an interest in compliant mechanisms. I also very much enjoyed your humor, and am grateful for the many times when you offered career advice. To Dr. Nenadic thank you for your kind words of encouragement whenever we would see each other, and for the pleasant conversations. To Dr. Washington thank you for your mentorship and guidance. I appreciated having the opportunity to talk about my career goals with you, and learn from your journey. Thank you for also providing insight into smart materials, and actuators that helped further shape my interest in them.

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“If I have seen any further than others, it is by standing upon the shoulders of giants”. During my time at the University of California, Irvine I truly felt that I stood on the shoulders of giants. Thank you everyone for all your help and the many others that I did not mention.

CURRICULUM VITAE

PhD in Mechanical & Aerospace Engineering (2020)
University of California – Irvine (Irvine – USA)
Thesis: Hand rehabilitation after stroke: understanding and optimizing the usage of wearable robotic technologies

MS in Mechanical & Aerospace Engineering (2018)
University of California – Irvine (Irvine – USA)
Thesis: Grip Amplifier: A Residual Force Control Strategy to Support Pinch Grip with a Minimalistic Hand Exoskeleton

BS in Mechanical Engineering (2015)
University of Maryland – Baltimore County (Baltimore – USA)

RESEARCH EXPERIENCE

Neuromechanics Lab, University of Colorado-Boulder, Boulder, CO (2015)
Using a robotic arm, I studied the subjective value placed on effort during movement as well as loss aversion in movement decision making. Using a MATLAB generated code that analyzed data collected throughout experiment.

Veterans Affairs, Maryland Exercise and Robotics Center of Excellence, University of Maryland Baltimore (2014)
Developed a wearable pelvic attachment that attached to an ankle robot that helped stabilize patients during walking and reduced unnecessary vibrations that were caused by the natural motion of walking.

Autonomous Robot Lab, Cornell University, Ithaca, NY (2012)
Manufactured a robotic frame to fit on to a Segway robot. The frame had multiple attachments on it that allowed for several different sensors to be mounted on to the robot. Using these sensors, I created a 2.5D terrain height map for an autonomous robot to use for navigation purposes using MATLAB, and C# programming.

TEACHING EXPERIENCE

University of California, Irvine (2019)
Position: **Teaching Assistant in Mechanical Systems Laboratory**
Activities: Assisted with constructing lectures as well as gave lectures for Mechanical Systems and Robotics, an undergraduate course averaging 300 students per semester. Led lab sections that included on average 40 students per section. Helped teach fellow teaching assistants how to perform the experiments that were a part of the upcoming lab sessions

University of California, Irvine (2018)
Position: **Teaching Assistant in Mechanical Systems Laboratory**
Activities: Lead laboratory, and quiz sections that supplement lectures. Grade assignments and examinations. Provided input into the development of assignments and exams

PUBLICATIONS

Journal Publications

Sanders Q, Chan V, Augsburger R, Cramer S, Reinkensmeyer D, Do A, "Feasibility of Wearable Grip Sensing for Home Hand Rehabilitation Early After Stroke", *IEEE Transactions on Neural Systems and Rehabilitation Engineering*

Journal Papers in Preparation

Sanders Q, Chan V, Stoller O, Reinkensmeyer D, "Isometric Force Control is Well-Preserved in Individuals with Chronic Stroke Despite Continued Impairment of Manual Dexterity and Grip Strength"

Sanders Q, Chan V, De Lucena DS, Stoller O, Reinkensmeyer D, "Robotic measures of proprioceptive and tactile deficits after stroke: their relationship to each other, and to motor function"

Sanders Q, Reinkensmeyer D, "IGRIP EX: A minimalistic hand exoskeleton controlled using residual isometric force control strategy"

Sanders Q, Chan V, Augsburger R, Cramer S, Reinekensmeyer D, Sharp K, "Home Hand Rehabilitation Using a Wearable Grip Sensor in the Acute Spinal Cord Injury Population"

REFERRED PROCEEDINGS

Sanders Q, Okita S, De Lucena DS, Smith BW, Lobo-Prat J, Reinkensmeyer D, "Design and Control of a Novel Grip Amplifier to Support Pinch Grip with a Minimalistic Soft Hand Exoskeleton", International *Conference on Biomedical Robotics and Biomechatronics 2018*

INVITED TALKS

DS de Lucena**, Q Sanders,** "Wearables for Hand Rehabilitation After Stroke: Extending Rehabilitation into the Community," WeaRACon, March 2019.

CONFERENCE ABSTRACTS AND PRESENTATIONS

Sanders. Q, Lobo-Prat J, Reinkensmeyer D, "Grip Amplifier: A Residual Force Control

Strategy to Support Pinch Grip with a Minimalistic Hand Exoskeleton", IEEE *Haptics Symposium 2018*

Professional Services

Transactions on Neural Systems & Rehabilitation Engineering
Position: **Ad-hoc Reviewer**
Activities: Review and support scientific peer-review process.

Journal of Neural Rehabilitation Engineering
Position: **Ad-hoc Reviewer, Editorial Board**
Activities: Assisted in the examination of incoming papers for quality and scope. Also assisted in the selection of Associate Editors to handle each publication. Review and support scientific peer-review process.

TECHNICAL SKILLS

Programming Languages: MATLAB, C, C++
Autodesk Eagle – PCB Design
SolidWorks
Ansys Workbench
Statistical Software: R, SPSS

ABSTRACT OF THE DISSERTATION

Hand Rehabilitation after Stroke: Understanding and Optimizing the Usage of Wearable Technologies

By

Quentin Sanders

Doctor of Philosophy in Mechanical and Aerospace Engineering

University of California, Irvine, 2020

Professor David J. Reinkensmeyer, Chair

The hand is a highly complex machine as evidenced by its mechanical structure and the large amount of cortical resources it requires for both sensation and motor control. Stroke is a pervasive, global problem that causes disability by damaging hand neural control systems. Movement practice can help drive the changes in neural connectivity needed to restore these systems, however, stroke patients typically undertake limited amounts of movement practice. The premise of this dissertation is that mechanical engineering techniques, and, specifically, the appropriate design of robotic therapy technologies based on an engineering-informed understanding of human hand mechanics and function, can improve the biomedical situation for individuals after a stroke.

Specifically, this dissertation addresses the question “How do we optimize the usage of wearable robotic technologies for hand rehabilitation after stroke?” Here we demonstrate progress in answering this question by considering three key areas: usership patterns of wearable hand sensing technology in real-world settings, sensory

and motor control of the hand after stroke, and the mechanical design and intuitive control of wearable soft robotic technologies for the hand.

Regarding usership patterns, we studied a simple wearable sensor – the MusicGlove – in the home setting with individuals in the sub-acute phase of stroke. We found that only 14% of stroke patients have enough residual function in the hand for sensor-only rehabilitation, motivating us to work toward a device that can offer robotic assistance. Further, we demonstrated a connection between machine failure theory and usership via the functional form of the statistical distribution of the amount of use. Finally, we observed that -- when left to self-adjust the parameters of their worn device -- people make logical decisions relating to challenge, suggesting the strategy of building rehabilitation devices that allow individuals freedom by which to adapt their own control strategies.

In the area of sensory and motor control we address two specific questions: How does isometric grip force control compare to other aspects of hand function after stroke, and how do sensory deficits measured robotically correlate to motor function after stroke? Through a series of experiments conducted with chronic stroke survivors we showed that isometric grip force control is not only a well preserved control signal after stroke, but is also more preserved than strength or manual dexterity. This provided the conceptual basis for a novel exoskeleton control strategy -- residual force control – in which isometric grip control by some fingers drivers full movement control of other fingers. Additionally, we showed sensory deficits, and, specifically, finger position sensing versus tactile deficits, are correlated with hand function after a stroke, suggesting the importance of developing devices that can retrain, promote, and challenge finger position sensing.

In the last area -- mechanical design and control – we integrated the above findings as follows. First, we developed a novel, compact, soft actuator capable of providing the biologically-scaled force and impedance that the large fraction of stroke survivors we identified needed to assist their finger movement practice. Second, we integrated this actuator into a form-fitting, minimalistic exoskeleton -- the IGRIP exoskeleton – that facilitates active sensory-based control of pinch grip using the residual force control strategy. Third, we tested the IGRIP exoskeleton with ten unimpaired individuals by substituting it for their index finger in a prosthesis-like mode. We found that these individuals were able to learn to incorporate finger sensory input in order to take advantage of the residual force control strategy, thereby improving their performance at a manual lifting task beyond levels achievable without active, sensory-based control. These advances define a potential path forward toward user-accepted, worn, therapeutic, assistive robotics for the hand after stroke.

CHAPTER 1. INTRODUCTION

1.1. HAND NEUROMECHANICS

The human hand represents one of the most complex and beautiful pieces of natural engineering within the human body. Our hands afford us the ability to interact with our environment in a multitude of ways, whether that's using a power grasp or cylindrical grasp to grab cups or lift objects, making a tripod grasp to hold a pencil and write with it, or simply using our hands to communicate with others. Our hands are one of the primary ways in which we interact with the natural world around us. The complexity of the hand is what makes it such a versatile instrument. The hand can be separated into five different components: the fingers, thumb, wrist, palm, and the opisthenar. Further breaking down the hand, the underlying mechanism consists of 19 bones that are connected in serial chains through revolute, and in some cases, spherical joints. The palm contains five metacarpal joints, and each finger except the thumb contains one proximal interphalangeal joint, one middle phalangeal joint, and one distal phalangeal joint. The thumb does not have a middle phalangeal joint, but instead has one interphalangeal joint, and one metacarpal joint. The thumb contains five degrees of freedom (DOF), and each finger has an additional four, in addition to the DOF present at the finger carpometacarpal joints (Fig. 1) [1].

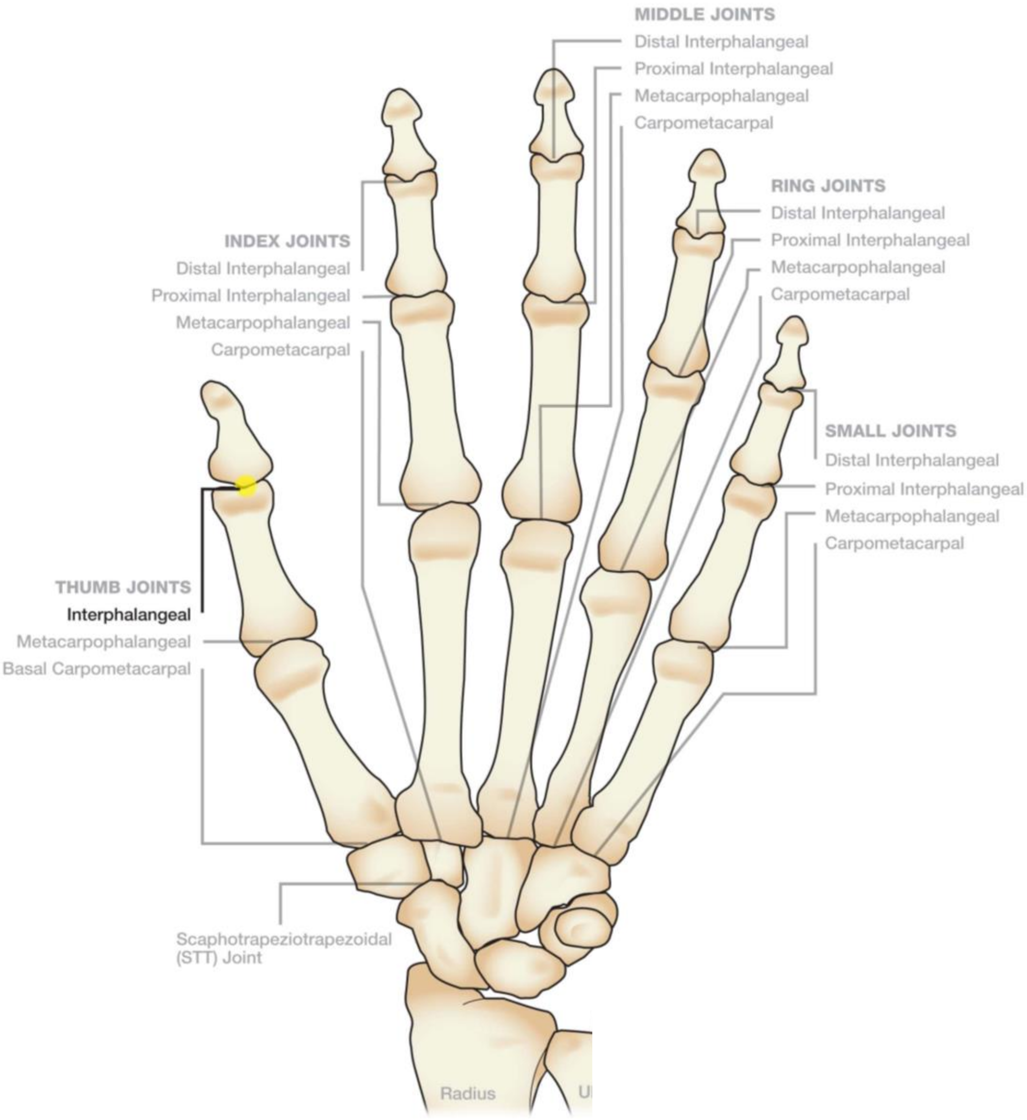

Figure 1. Joints in the human hand

This total of 21 DOF are controlled by 27 muscles; 8 extrinsic muscles which are located mainly in the forearm proximal to the wrist and connect through long tendons, but also 19 muscles in the hand itself (intrinsic muscles)**.** Flexion of the fingers is produced by two extrinsic muscles; the flexor digitorum profundus, and the flexor digitorum superficialis which are connected to the finger bone structure via tendons**.** The extensor digitorum, another extrinsic muscle of the hand, is also connected to the fingers via tendons and is responsible for extension of the fingers (Fig. 2) [1].

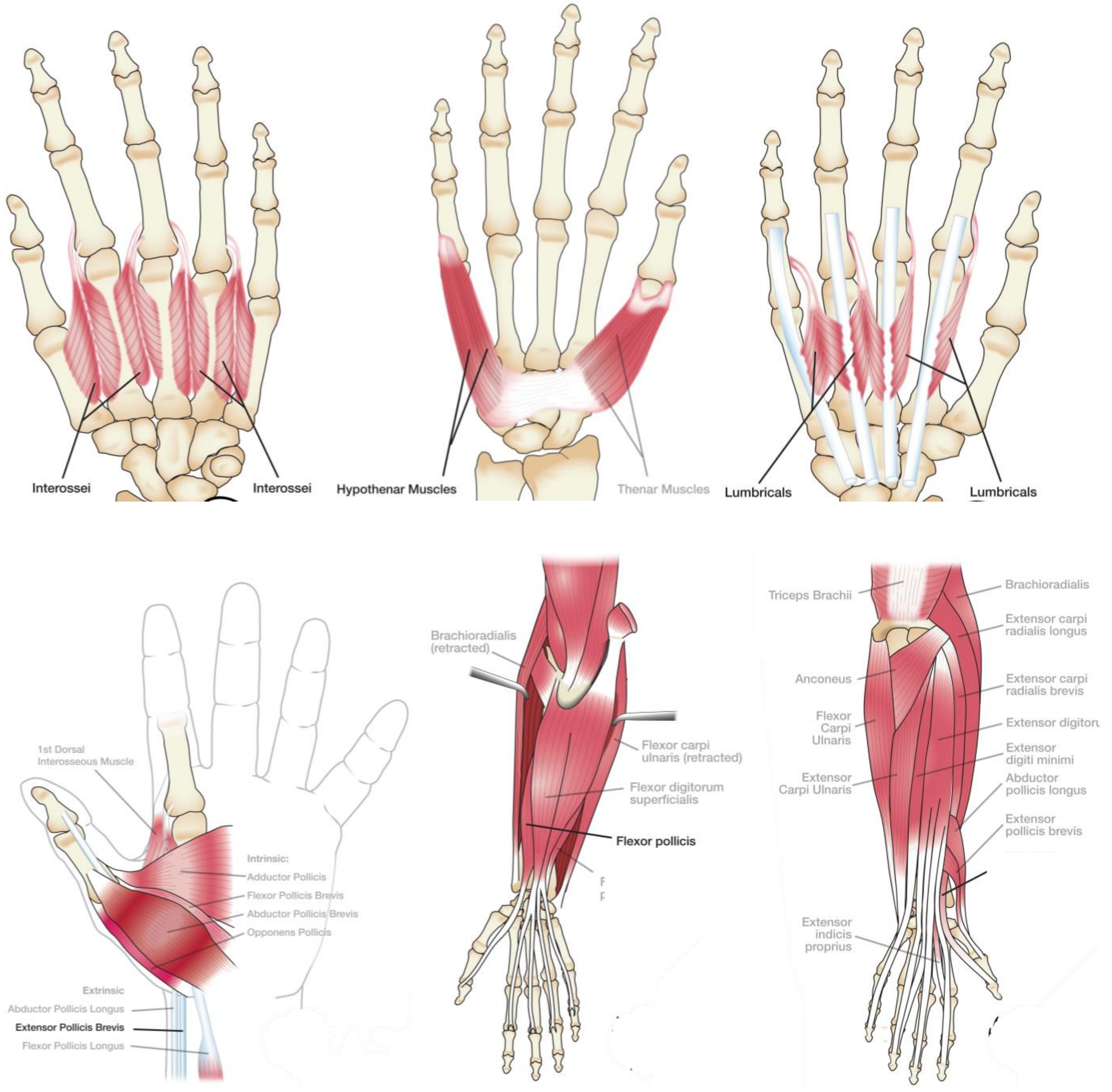

Figure 2: Intrinsic (top row) and extrinsic muscles (bottom row) of the hand. The intrinsic muscles lie within the hand itself while the extrinsic muscles have muscle bellies that lie in the forearm.

The biomechanics of the hand again are what make it such a versatile instrument. However, the high complexity of the hand comes with a computational cost. That is, control of a highly sensate organ with a large number of degrees of freedom requires a substantial amount of cortical resources. This is evidenced by the representation of the hand in comparison to other parts of the human body on both the somatosensory and motor homunculi. (Fig 3.).

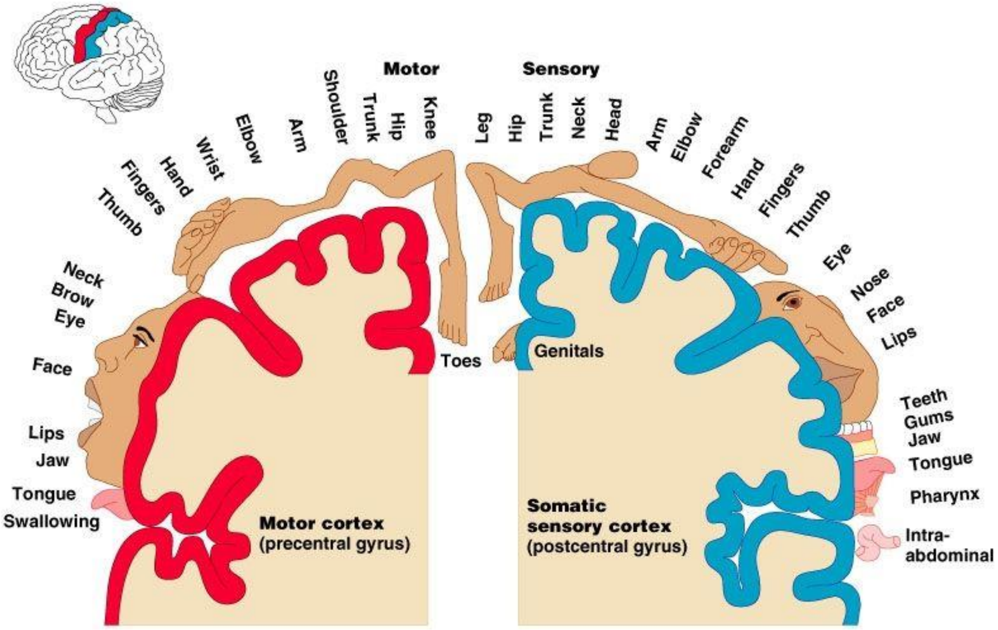

Figure 3. Cortical Homunculus. There are two cortical homunculi: a motor homunculus, and a sensory homunculus. Each of the homunculi are a visual representation of the human body based on a neurological "map" of the areas and proportions of the human brain that are dedicated to processing motor or sensory function for different parts of the body.

The reliance on cortical projections for both motor commands and sensory feedback causes the hand to be significantly impacted by injuries to the central nervous system such as those produced by stroke or spinal cord injury. Also, regarding ischemic strokes, the manner in which the arterial blood supply bifurcates is another factor that leads to motor function becoming severely impacted after stroke. When an individual is suffering from a stroke blood clots get stuck in the middle cerebral artery bifurcation, which causes strokes of the motor area.

1.2. SENSORY AND MOTOR FUNCTION OF THE HAND AFTER STROKE

Stroke, produced by either hemorrhage (~20% of strokes) or occlusion (~80% strokes) of blood vessels in the brain, is the leading cause of major long-term disability within the United States. Almost 800,000 Americans experience a stroke each year, and worldwide an estimated 15 million strokes occur each year [2]. It is estimated that 1 in 6 people worldwide will experience a stroke [2].

Stroke can have an impact on several different bodily functions, varying from speech, to vision, to sensorimotor control of the limbs. This latter problem – motor control is especial common: approximately 80% of persons in the early phase of stroke experience upper extremity impairment, especially in the hand. This hand impairment typically manifests primarily on one side of the body, although manual function of the other side is often quantifiably reduced [3], [4]. After six months post stroke it is reported that approximately 50% of patients remain with a chronic reduction in arm-hand function.

The severity of hand impairment in persons with stroke can vary widely with deficits in hand function arising from a range of different sources. For example, after a stroke an individual can potentially experience impairments to the somatosensory system, flexor hypertonicity, reduced and aberrant muscle activation, abnormal muscle tone, or loss of finger individuation. Impairments to the somatosensory system can include a variety of things such as impaired proprioception, tactile discriminatio**n**, tactile localization, stereognosi**s**, or the ability to detect changes in temperature [5]–[8]. Somatosensory data is essential for fine motor control of the hand and is thought to play a key role in motor learning [9]. Hypertonicity after a stroke can manifest as spasticity, excessive coactivation, and prolonged relaxation time of the long finger flexor muscles [1]. Spasticity is defined as velocity-dependent increase in muscle tone that manifests with resistance to passive movement, and is thought to arise from a disinhibited and thus hyperactive stretch reflex [1], [10].

During active movement, problems with muscle activation control may manifest in different ways. For example, attempting to open the hand using long finger extensors may result in net finger flexion due to excessive coactivation of the finger flexors [11]. This makes opening the hand to position it around an object very difficult for persons with stroke**.** The ability to release an object may also be affected as deactivation of the finger flexors may be abnormal as it has been shown that there is a noticeable increase in the amount of time it takes to relax the finger flexor muscles after grasping an object [12]. In addition to hypertonia, weakness is prevalent in the hand after stroke. Even in moderately impaired persons with stroke, grip strength in the impaired hand is only 50% of that of the unimpaired hand [13]–[16]. Abnormal synergy patterns can also develop after stroke. For example, it is common for individuals who have suffered from a stroke to develop a flexor synergy pattern in the initial phase following stroke. A flexor synergy pattern typically consists of external rotation of the shoulder, flexion of the elbow, supination of the forearm, and wrist and finger flexion [17]. This flexor synergy that is apparent after stroke inhibits an individual’s ability to independently move the fingers which can significantly degrade the individual’s ability to perform complex motor tasks (Fig. 4)**.**

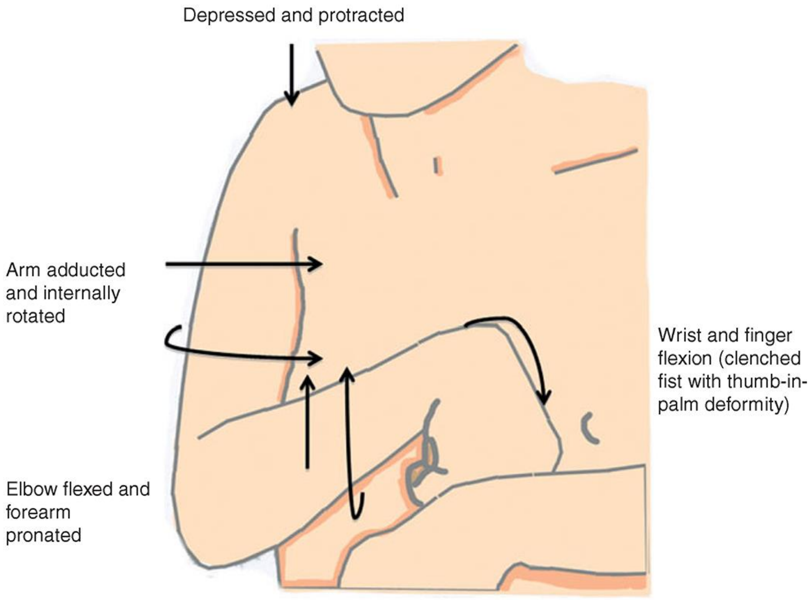

Figure 4. Typical presentation of an individual who has suffered a stroke.

1.3. HAND REHABILITATION AFTER STROKE

1.3.1. Activity-dependent neuroplasticity of the brain after stroke

The human brain has quite the amazing ability to learn and adapt as we go on throughout life. This is evidenced in our ability to learn complex motor tasks at various stages of our life such as learning to ride a bicycle as a child or learning to cook perhaps as a young adult. This remarkable ability of the brain to modulate and form new neural connections as we develop skills and grow is known as neuroplasticity [18]–[22]**.** This ability to adapt neural connections remains viable after a neurological injury such as stroke or spinal cord injury. Further, after a neurological injury, individuals often experience a massive reorganization of cortical and subcortical function**.** Although a significant portion of motor function recovery due to this reorganization is spontaneous , motor practice can enhance the effects of neuroplasticity [23]–[25]**.**

1.3.2. Traditional approaches to rehabilitation after stroke

Typically, after a stroke, an individual will often undergo several months of rehabilitation therapy to improve motor function. Rehabilitation may consist of several different strategies, including task-specific training, strength training, or other forms of functional movement training oriented at reducing tone or improving soft tissue compliance. These sessions also typically ask the patient to focus on attempting to generate high-quality or biomechanically correct movements, based on the idea that practicing low-quality, or compensatory type movement, will lead to sub-optimal recovery. For example, during a reaching task in the initial phase following stroke patients may lean the trunk forward until their affected arm is in a position to reach an object instead of fully extending their affected arm to the object. This promotes disuse of the affected arm to complete the task, and over reliance on this type of strategy could limit recovery as the patient could start relying on this movement instead of attempting to use their affected arm.

There have been some studies that have shown the benefits of rehabilitation in the traditional setting, however the number of movement repetitions typically achieved during these sessions are small. For example, over a series of studies that were observed with both spinal cord injury patients as well as stroke patients the average number of repetitions that were completed was approximately 40 [26]**.** In comparison, using rodent models of motor recovery after stroke, it has been shown that many thousands of movements are necessary to begin to facilitate forelimb recovery after a neurological injury [27], [28]**.**

What limits the amount of practice accomplished during therapy? One limit is the focus on high-quality of movement, which typically requires performing a movement slowly, with appropriate kinematics. This requires a high level coaching and that the patient provide intense focus of attention, factors that slow down practice. Increased susceptibility to both muscular and mental fatigue also likely plays a factor, especially early after a stroke. A third factor is that therapists, like coaches of sports, typically view their one-one-one sessions more as advice sessions. They, expect, then, that patients will practice what they have learned on their own at high volume. However, patients typically show low-compliance to assigned movement practice “homework” [29], [30].

These challenges thus raise the question of how best can stroke rehabilitation researchers increase the number of movements necessary to facilitate recovery while also making the therapy engaging to the user. To address these needs researchers have explored technological approaches, such as the use of robots to try to enhance stroke rehabilitation.

1.4. ROBOTICS FOR HAND REHABILITATION AFTER STROKE

Over the past two decades there has been a dramatic increase in the development and use of robotics for rehabilitation purposes. This increase in robotic technologies is likely due to several factors. Many of robotic systems have shown therapy outcomes that are comparable to equivalent intensive movement training without robotic aid or an equal number of unassisted movements, suggesting that robotic training can provide intensive therapy at lower cost and effort [31]–[34] **.** Robotic devices can also be used to evaluate progress quantitatively, can help the user generate a high number of repetitions during therapy, and can help assist the user in making movements that they normally could not make, which promotes beneficial neural plasticity and improve motivation for therapy [35]**.**

These robotic devices can take a variety of different forms from exoskeletons in which there is patient-robot alignment of the joints to end effector based robotic devices in which movements are generated from the most distal segment of the extremity, and there is no alignment between patient-robot joints. However, for hand rehabilitation devices involving finger motion, the exoskeleton approach has mainly been taken to fit to the relatively small and complex structures of the hand, compared with that of the arm.

However, designing hand exoskeleton devices is a challenging task due to the complexity and versatility of the human hand. This is evidenced by the number of exoskeleton devices that have failed to undergo testing with their target population with most testing of such devices occurring in a laboratory setting, and not in the home environment. 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 [36]. But of these systems only 25 % of the devices had undergone any sort of testing with people with a stroke . A similar trend can be seen in a more recent review conducted in 2016. In this review over 165 hand exoskeleton devices were identified, yet only 10% of these devices had performed any testing with persons with stroke [37].

Why are engineers designing complex robotic rehabilitation devices but then failing to test them with patients? In planning this dissertation work, two key reasons were identified. First, is a lack of methods for intuitive control. It currently remains a challenge to provide intuitive and robust control of a hand exoskeleton. In a review conducted in 2016, over 165 dynamic hand orthosis or hand exoskeletons were identified [38]. In this review the primary control strategies incorporated were using surface electromyography (sEMG) or the activation of a switch. However, using a switch requires using the non-affected hand to trigger movement of the affected hand. There has been some level of success with the implementation of sEMG. For example, the Myo Pro Orthosis is a commercial hand-arm exoskeleton that incorporates sEMG. But it should be noted that when using sEMG the signal can be affected by electrode placement, and artifacts within the signal such as those caused by hair on the skin or sweat. Other forms of intent recognition such as mechanomyogram, force myography, or electroencephalogram are still in the experimental phase of research and possess limitations that make them impractical for routine use.

A second reason exoskeletons are often not tested with their target population is because of their mechanical design. Many exoskeletons choose to focus on actuating all the fingers in a power grasp. As a result, most devices are heavy, complex, and bulky – to the extent that they become difficult to don and wear. And yet, there does not appear to exist a rigorous rationale for this design choice. For example, there are other possible grip types that could be assisted, which would result in different exoskeleton topologies. An ecological study of a professional house maid and professional machinist using a head-mounted camera found that they each used power grasp in only 27% and 11% of the instances of gripping recorded throughout their days, splitting time using six or nine (respectively) other types of grips, including thumb-index pinch grip and lateral pinch grip [39]–[41]. Increasing the portability, and simplicity of exoskeleton devices could lead to therapy that could be performed in a clinical setting, but also in the home-setting as well which could have several benefits. For example, at-home rehabilitation has the potential to increase the number of repetitions a person is receiving outside of the clinical space. Also, home-based technologies have the advantage of providing the patient flexibility with the location and time of rehabilitation therapy.

1.5. ROBOTICS VERSUS SENSOR-BASED REHABILITATION FOR HAND REHABILITATION IN THE HOME SETTING

There have been several attempts to try to develop technology for rehabilitation in the home setting outside of robotics. Researchers have suggested the used of telerehabilitation which uses information and telecommunication technologies such as a telephone or video conferencing to help patients receive medical services from a health provider remotely**.** Other technologies include sensors, tablets and mobile devices, and virtually reality systems [42]**.** Although each of these devices has seen some level of success, each possesses limitations that have prevented widespread use and translation into the market. Using tablets can be challenging for stroke survivors with motor deficits. Sensors such as the Kinect or Wii remote often have issues with simulation accuracy of movements that are not advantageous to the game system itself. For example, in a review discussing the feasibility of the Kinect for stroke rehabilitation that included more than 22 studies it was shown that the Kinect has reasonable accuracy as compared to other motion capture systems when examining large gross movements [43]. However, the Kinect was unable to capture fine motor skills without the use of other sensors. Additionally, the Kinect was not able to accurately capture gross movements that remain extremely small in their entirety making it difficult to use the system with severely disabled patients **.**

With telerehabilitation, a missing factor is the physical interaction between the patient and the therapist. Additionally, there are uncertainties regarding policies such as privacy, and cost among others. With virtual reality approaches there have been some studies that have reported benefits to upper extremity rehabilitation, but the evidence remains inconclusive [44]–[46]. As there are also studies that have shown little benefit from virtual reality training. Furthermore, it is also not well understood how improvement in the virtual reality space translates to gains in reality, as it has been shown that how the brain processes information in virtual reality settings differs from how the brain processes information in reality [42]**.**

In our lab we have demonstrated the viability of an instrumented glove to administer hand rehabilitation therapy in the home setting using music (the MusicGlove). The instrumented glove has sensors on the fingertips, and later aspect of the index finger. To play the game subjects make gripping movements in time with notes that are displayed on the screen similar to the video game Guitar Hero. When performing home-based training by persons in the chronic phase of stroke with the MusicGlove device individuals showed significantly greater improvements in self-reported functional use of the impaired hand. Users of the device also completed many more movements than what was asked indicating a high level of motivation to use the device [47]–[49].

Sensor-based rehabilitation approaches like the MusicGlove device have been designed in such a way that they are not as obtrusive as their exoskeletal counterparts enabling us to perform rehabilitation in the home setting. However, one limitation of sensor-based rehabilitation is that they require a moderate level of hand function to operate. With the MusicGlove for example, subjects must actively move their fingers, making the appropriate gripping movements in order to play the game. This limits the feasibility of wearable sensors with patients who are more severely impaired. For example, in a study conducted with the Raphael smart glove another commercially available movement sensor for hand rehabilitation 110 patients were screened. Of those patients screened only 14 patients qualified for enrollment in the study [50]**.**

1.6. OUTLINE OF DISSERTATION

Stroke often severely impacts hand function. This makes developing effective techniques for rehabilitation of the hand critical to restore independence and increase quality of life after stroke. At present, robotics technologies for hand rehabilitation – defined broadly as actuators, sensors, and computation that interface with the hand – have seen limited adoption in clinical and home settings. The lack of adoption of these technologies in both clinical and home settings we think can be attributed to four key issues. The first is that at present it remains a challenge on how best to detect user intention. Second is in their current form robotic technologies remain overly bulky and obtrusive devices. Third there is a lack of consideration of sensory deficit after stroke. Finally, there is a lack in understanding of the usership needs and patterns of these devices if they were available for use in the home setting (Fig. 5).

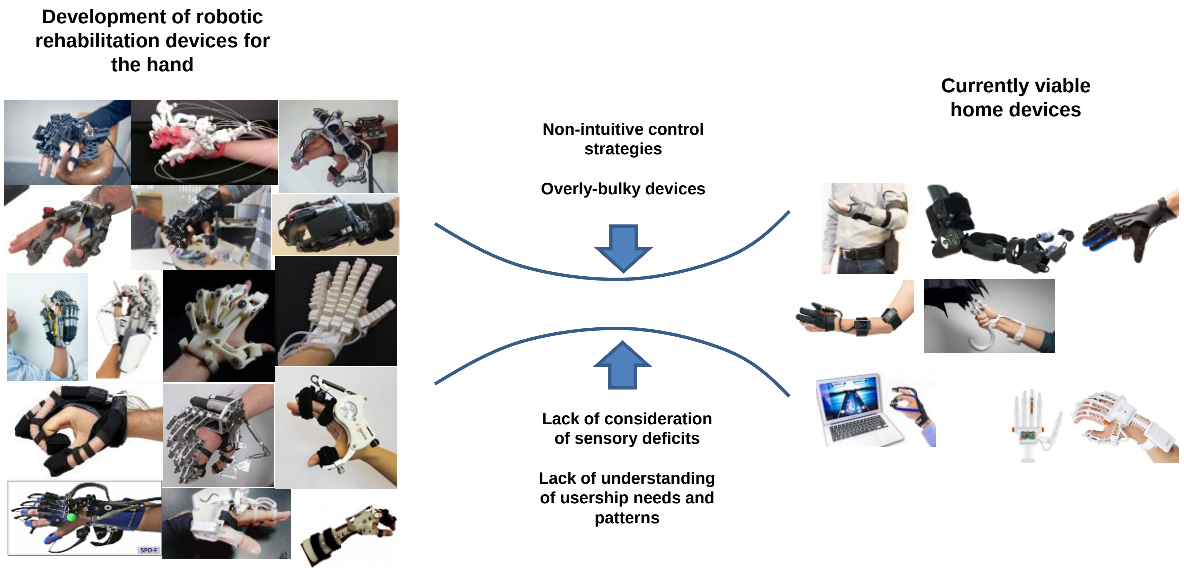

Figure 5. On the left side are a number of exoskeleton devices that have been designed over the last decade. However, many of these devices have failed to be tested outside of a laboratory setting, and have seen limited adoption in the clinical or home space due to a number of issues. On the right are sensor based and robotic devices for hand rehabilitation after stroke that have been able to pass through this “bottleneck” , and are commercially available devices that have seen application in the clinical space and in the home space.

This dissertation focuses on addressing the question “How do we optimize the usage of robotic technologies for hand rehabilitation after stroke” particularly for patients who are more severely impaired. Progress is made in answering this question by considering three areas:

1) better understanding how sensory motor control is compromised after stroke;

2) identifying for the first time usership patterns of wearable hand sensing technology in the home setting;

3) improving the mechanical design and intuitive control of wearable robots for the hand.

We considered these three areas for several reasons. First, gaining a better understanding of the aspects of motor control that are preserved in the hand after stroke could provide insight into the types of movements that can still be performed, and how well stroke survivors can control these movements. This could lead to the development of control strategies that involve the impaired limb instead which could be more intuitive than using the unimpaired limb as a control source, and offer an alternative to surface electromyography which although it does involve the impaired limb presents other challenges that limit its application in commercial products. Second, improving our knowledge of sensory deficits, and further our understanding of how these deficits relate to motor function after stroke can help determine whether or not robotic devices for hand rehabilitation need to include ways to retrain, promote, and challenge sensory deficits. As many devices currently do not include ways to retrain, or challenge sensory deficits which could be potentially limiting their therapeutic benefits. Third, rehabilitation in the home setting offers a way to provide individuals that chance to increase their movement practice which can help facilitate motor recovery. This requires the design of devices that are portable, robust, and intuitive. However, even the most well designed devices can go unused for myriad of reasons. Thus, it is imperative that we understand how users would use devices in the home-setting as this would allow us to understand what factors influence user engagement and how users modulate various parameters of the given device. This information in turn then could help improve the mechanical design of devices as well as the control strategies incorporated to better account for these factors. Finally, as mentioned previously two of the key issues that limit adoption of robotic technologies in the home setting, or the clinical setting is the lack of intuitive control and the bulkiness of current devices. Non – intuitive strategies can be cognitively demanding, and make the device difficult to use. While bulking, and obtrusive devices, may be heavy which could interfere with the completion of movements, making it difficult to execute tasks. The weight of the devices if used for long duration of time could also fatigue the hands. Thus by improving the mechanical design and control of robotic technologies we could increase the usage of the device which could potentially lead to improved therapeutic benefits. In summary, we have provided the rationale for why we think progress in those three areas is key in optimizing the usage of robotic technologies, and now will discuss the structure of the dissertation.

In CHAPTER 2 of this dissertation we discuss the usership patterns of wearable sensing technology during home-use. As described above, robotic technologies for hand rehabilitation have as yet seen limited use at home. Therefore, it is at present difficult to understand how users would actually use these technologies, were they available. Recently, our laboratory developed a simple wearable sensor – the MusicGlove – that has seen viability for home use, becoming a commercially available device used at home by over 1000 people. In this part of the dissertation, as part of a usability study of the MusicGlove, we sought to understand several questions:

1) What percent of stroke survivors can use a sensing-only solution for hand therapy?
2) What levels of activity do they achieve and how does those levels fall off over time?
3) Do users self-adjust difficulty in a logical way to challenge themselves?

In the aforementioned study individuals could freely adjust the game parameters which made the game either more or less challenging. Additionally during the study, patients were separated into two different groups; a control group. The experimental group received the wearable grip sensor first, while the control group received a standard booklet of exercises for hand therapy. Both groups were instructed to perform therapy for three weeks with their given intervention. After this time individuals switched and practiced with the other intervention for an additional three-week period.

Regarding the sensory and motor function of the hand after stroke we posed two questions. First, what is the most-preserved aspect of hand function after stroke? (CHAPTER 3). Understanding this could provide a more rational basis for developing intuitive control strategies for robotic hand exoskeletons. Previous research has suggested that the ability to isometrically flex the fingers remains relative intact after stroke, but it is unknown how this ability compares to other aspects of hand function. We assessed isometric, flexion, grip force control using a robotic platform that included a force transducer and a grip force tracking game. For comparison, we also measured grip strength, as well as manual dexterity in the hand using two different standard clinical assessments. For each measure of hand function, we calculated an impairment ratio, defined as the impaired score divided by the unimpaired score.

Second, how important is somatosensation for hand function after stroke? As described above, somatosensory deficits are common after stroke, and somatosensation is thought to be highly important for normal hand function. Yet, most robotic hand therapy devices for the hand focus on training the motor aspects of hand control. To address this second question, we determined the strength of the correlation between measures of somatosensory deficits and motor function after stroke (CHAPTER 4). Several previous clinical studies have examined this question, but using coarse clinical measures of somatosensory deficits. Here, we conducted a study with twenty subjects with chronic stroke in which we measured their finger proprioceptive ability using a tabletop hand exoskeleton. We also measured subject's finger tactile discrimination ability using a cell phone. For both measures we assessed their relationship with two clinical assessments that evaluate hand function after stroke.

In CHAPTER 5 we use the results from the studies conducted in CHAPTERS 2-4 to shape the design of a hand exoskeleton control strategy. We prototyped and tested the control strategy with a tabletop hand exoskeleton, first with unimpaired subjects . We asked, can unimpaired subjects learn to intuitively use the control strategy, could subjects modulate their use of the strategy with feedback, and how does the new control strategy affect normal grip force modulation strategy used during object manipulation. Finally, we implemented this control strategy on a novel, minimalistic hand exoskeleton that incorporates an innovative compliant actuator (CHAPTER 6). We discuss the fabrication process for this compliant actuator, and characterize its performance. We also discuss the advantages and disadvantages of the current design of the actuator and present preliminary data obtained from testing the hand exoskeleton with unimpaired subjects.

CHAPTER 7 reviews the main contributions of this work and discusses directions for future research.

CHAPTER 2. WEARABLE SENSING FOR IN-HOME FINGER REHABILITATION EARLY AFTER STROKE

2.1. INTRODUCTION

Upper limb sensorimotor function is severely impacted after stroke with about 80% of patients experiencing deficits early after symptom onset. Additionally, upper limb impairment persists in about 60% of patients 6 months post-stroke [51]. Intensive movement practice can help reduce hand impairment after stroke [52]–[57], but cost and accessibility limit an individual's ability to reach the high number of task repetitions thought necessary to improve recovery [24], [26], [27].

Home-based rehabilitation programs have been prescribed after stroke with the intent to increase the amount of rehabilitation exercise individuals can perform. The most common approach to home-based therapy is following a printed handout of exercises prescribed by a therapist. But, compliance with performing a list of exercises prescribed for in-home rehabilitation therapy is poor across a wide range of exercise types [29], [30], [58]–[60]. Thus, a critical outstanding question is how to motivate stroke patients to exercise in the home setting.

Several studies in the chronic phase (> 6 months post stroke) after stroke [60]–[64] have examined different strategies for in-home hand rehabilitation with mixed results. Modified constraint-induced movement therapy performed under the supervision of a nonprofessional coach in the home setting produced similar benefits compared to a program performed with a trained therapist in a clinical setting [61]. Greater self-reported use of the impaired limb in comparison to conventional therapy [62] was also observed. Another approach is tele-rehabilitation, which enables a therapist to guide training remotely. A systematic review of 10 trials with 933 total subjects found insufficient evidence to reach any substantial conclusions about the effectiveness of tele-rehabilitation after stroke, and most of these studies were applied in the chronic phase of stroke [65]. However, a recent study suggested that home-based telerehabilitation with a sensor-based system [66] that encouraged upper extremity movement practice following subacute stroke was not inferior to in-clinic training [64]. Other approaches to home-based hand rehabilitation include functional electrical stimulation [67], computer gaming with custom devices [68]–[70], and music-based therapy [71].

Despite the variety of options, it is still unclear which methods are the most viable for providing hand rehabilitation training at home, particularly early after a stroke (defined here as the first six months post stroke). Previous studies have shown that wearable movement sensors coupled with computer games can be motivating for rehabilitation [69], [72]–[74]. We explored this concept further by developing the MusicGlove device, an instrumented glove with sensors on each of the fingertips and the lateral aspect of the index finger (Fig. 6) [47], [75]. Home-based training by persons in the chronic phase of stroke led to significantly greater improvements in self-reported functional use of the impaired hand [49].

Figure 6. MusicGlove device used in study. Users viewed a musical computer game that visually cued them using scrolling notes to make specific gripping movements in time with the notes. The device detects the movements using conductive finger pads. For the present study, the game was played on a 9 in. tablet computer.

The present study sought to evaluate the feasibility of the MusicGlove as a home-based rehabilitation tool for individuals in the subacute period following stroke. Using such a wearable sensor soon after stroke at home raises several questions. First, as with many wearable sensors for hand rehabilitation, users need a moderate level of preserved hand function to effectively operate the MusicGlove. Users must be able to self-don it at home and complete the required gripping movements to play the associated computer game. Hence, the first feasibility goal of this study was to determine the fraction of individuals in the subacute phase of stroke who had adequate hand function to use such a wearable grip sensing approach.

Second, individuals in the subacute phase of stroke have just experienced a major life-changing event and are typically receiving standard-of-care rehabilitation therapy. They often have more medical appointments than people in the chronic phase after stroke, which might influence motivation to participate in additional therapies. A second feasibility goal was to determine if individuals in this population would use the MusicGlove as much as people in the chronic phase, as measured in an identical study protocol [49].

Third, a concern about self-administered care in the home setting is whether patients will appropriately challenge themselves. We therefore sought to characterize how users chose the game parameters that determined the challenge they experienced as they played.

Finally, we sought to establish a preliminary estimate of the effect of MusicGlove use on hand function in subacute stroke.

2.2. METHODS

2.2.1. STUDY DESIGN, RECRUITMENT, AND INCLUSION CRITERIA

The University of California, Irvine (UCI) Institutional Review Board approved this randomized, controlled single-blind cross-over study, and all subjects provided informed consent prior to enrollment in the study. The study was designed to compare self-guided exercise with the MusicGlove to self-guided conventional hand therapy, both performed in the participant's home. The study was registered at ClinicalTrials.gov (NCT02410629). We included a control group because the original intent was to determine the therapeutic effect of MusicGlove. However, budgetary constraints and slow recruitment limited sample size, causing us to focus in this paper on feasibility rather than therapeutic results. Subjects were recruited by fliers distributed to local rehabilitation programs and by screening all new stroke subjects admitted at the UCI Medical Center. The inclusion criteria for the study are shown in Table I. Note that Table 1 contains more detail about the final cutoffs used for various impairments in comparison to the table presented on ClincialTrials.gov. Potential subjects who did not qualify for the study were re-assessed after a few weeks to determine if their hand recovery progressed to a level that would allow them to participate.

TABLE I

INCLUSION CRITERIA

18 to 80 years of age
History of stroke affecting the hand
Between 1-10 weeks post-stroke
Upper extremity weakness, defined as score of 15-62 (out of 66) on the Upper Extremity Fugl-Meyer Test
Able to perform at least 3 blocks on the Box and Blocks Test (BBT) but not greater than 80% of the score of the non-affected hand on the BBT
No other active major neurological disease other than stroke
Absence of severe pain in the stroke-affected upper extremity – score ≤ 3 on Visual Analog Pain scale
Absence of severe spasticity or contractures at the affected upper extremity (score <4 on the Modified Ashworth Scale)
Absence of severe aphasia
Absence of severe reduction in level of consciousness
Absence of severe sensory / proprioception deficit at the affected upper extremity (score of 0 in all categories of the Fugl-Meyer Sensory Examination)
Not currently pregnant
No active major psychiatric problems, or neurological/orthopedic problems affecting the stroke affected upper extremity
No difficulty in understanding or complying with instructions given by the experimenter
Able to perform the experimental task

2.2.2. GROUP ASSIGNMENT AND INTERVENTION

In this cross-over design, a total of 11 subjects were randomized to receive either MusicGlove therapy first (MG 1st group) or conventional therapy (MG 2nd group) (Fig. 7).

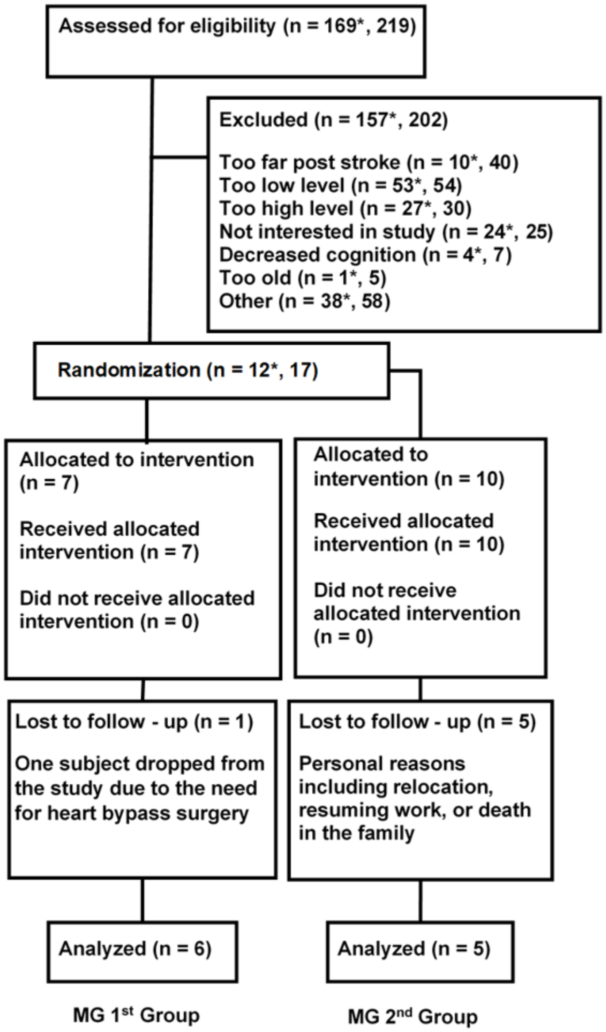

Figure 7. Consolidated Standards of Reporting Trials Diagram. * denotes numbers from consecutively enrolled patients to a single hospital; the total number from all recruitment sources is shown as well.

To ensure matched levels of impairment between groups, subjects were first stratified by their Box and Blocks Test (BBT) baseline score (3–30 or 30–60) and then assigned to a group by adaptive randomization [76]. The BBT is an established clinical measure of hand function that measures the number of blocks an individual can pick up and move over a divider in one minute; a normal score is about 60 blocks/min [77]. The MG 2nd group was trained to follow a booklet of conventional hand exercises [49] while the MG

1st group was trained to use a MusicGlove and tablet computer (Fig. 6) as their first intervention; training took about 30 minutes.

In the initial training session, the project therapist showed subjects how to play the game, including changing game difficulty parameters and how changing the parameters affected the game. The therapist also instructed subjects that they were free to change the difficulty of the games as they wished. When the subjects took the MusicGlove home, they started at whatever difficulty setting they chose. Subjects were asked to perform at least three hours of their intervention per week for three weeks.

Subjects were free to modulate the difficulty of their MusicGlove training by changing the number of grip types (1-5: lateral pinch, index-thumb, middle-thumb, ring-thumb, pinky-thumb grips) needed to play, and/or by selecting songs at three different difficulty levels, where difficulty was determined by the number of target notes per minute of song. Subjects were also free to choose whether to play the game in “Song Mode” or “Session Mode”. In “Session Mode”, several songs at the same difficulty level are played in series and subjects can make changes to the game parameters after the series of songs has ended. Subjects could select series of 15, 30, 45, or 60 minutes in length. In “Song Mode” subjects could modify game parameters after each individually selected song.

After the 3-week exercise period, the participants returned for a post therapy assessment, at which they returned the MusicGlove device or booklet of hand exercises. Then, after another 3-week period, they returned for the 3-wk follow-up assessment, followed by an assessment when they were 16-weeks post-stroke. At the 16-wk follow-up, individuals in the MG 2nd group were given the MusicGlove to use while individuals in the MG 1st group were given a booklet of hand therapy exercises. Each group matched the previous protocol, used the given intervention for three weeks, ceased activity for 3 weeks, and then returned for their follow-up at 6 months post stroke. During this study subjects received simultaneous rehabilitation therapy as part of their standard-of-care treatment. We did not control for the amount or content of this treatment as we deemed it both impractical and unethical.

2.2.3. OUTCOME MEASUREMENTS

An experienced, blinded rehabilitation therapist performed a set of clinical assessments at baseline and at each additional time point during the study. We choose the follow-up periods (16-wk post-stroke, 6 months post-stroke) with respect to the onset of stroke as opposed to start of intervention in order to minimize the variance caused by spontaneous recovery, since the rate of spontaneous recovery varies depending on the time post stroke. The BBT score evaluated at the 3-wk post-intervention follow-up was preregistered on clinicaltrials.gov as the primary outcome measure. This paper focuses on this clinical measure of hand function only.

2.2.4. DATA ANALYSIS

We analyzed the data from periods of use of the MusicGlove device for usership metrics for each subject including: the success rate (# of notes completed / # of notes presented), amount of practice (as measured by the # of grips presented and the total usage time), and the types of in-game adjustments (i.e. changing song difficulty or grip types used). We assessed the distribution of the amount of grip practice by rank-ordering subjects, a common approach in non-parametric statistics. We used the R package *fitdistrplus* [78] to fit probability distributions to the data, and used Akaike Information Criterion (AIC) to evaluate goodness of fit.

We tested whether the probability of making a parameter change on the next song depended on the level of success achieved with the previous song using linear regression. For this analysis, we considered only songs that were not already at the lowest or highest difficulty levels. If the user increased the difficulty of one or both game parameters, we classified that as increasing game difficulty, and vice versa. Instances in which users increased one parameter and decreased the other were treated as no change in difficulty. The probability of changing the difficulty of the game was calculated for ranges of success using a sliding window of 10 jumping by 2 (i.e. success of previous song was between 0-10, then 2-12, etc.). Usership analyses were first applied to individual subjects, then averaged across all subjects.

2.3. RESULTS

2.3.1. FRACTION OF SUBACUTE STROKE PATIENTS SUITABLE FOR DEVICE

A total of 219 potential subjects were screened; 169 of these were stroke patients at a single university hospital and were available to enroll in the study (Fig. 7). Considering the consecutively screened stroke patients only, 92 met all other inclusion/exclusion criteria (Table I) before considering level of hand impairment. However, when considering hand impairment, 58% (53) of the consecutively screened potential subjects had too little hand function, 29% (27) had too high hand function, and 13% (12) had an appropriate level of hand function and enrolled in the study. Five subjects referred from other hospitals also enrolled, for a total of 17.

Five subjects withdrew from the MG 1st group due to personal reasons including moving to a different country, resuming work, or a death in the family. One more subject withdrew from the MG 2nd group due to the need to undergo heart surgery. Thus, there were a total of six subjects in the MG 1st group and five in the MG 2nd group who completed all research procedures.

2.3.2. USAGE PATTERNS: AMOUNT OF USE

The MusicGlove computer logs revealed that the 11 subjects used the device on average 4.1 (+/- 3.2 SD) hours, which was 46% of the recommended 9 hours, and completed on average a total of 8627 (+/- 7500 SD) grips (Figure 8).

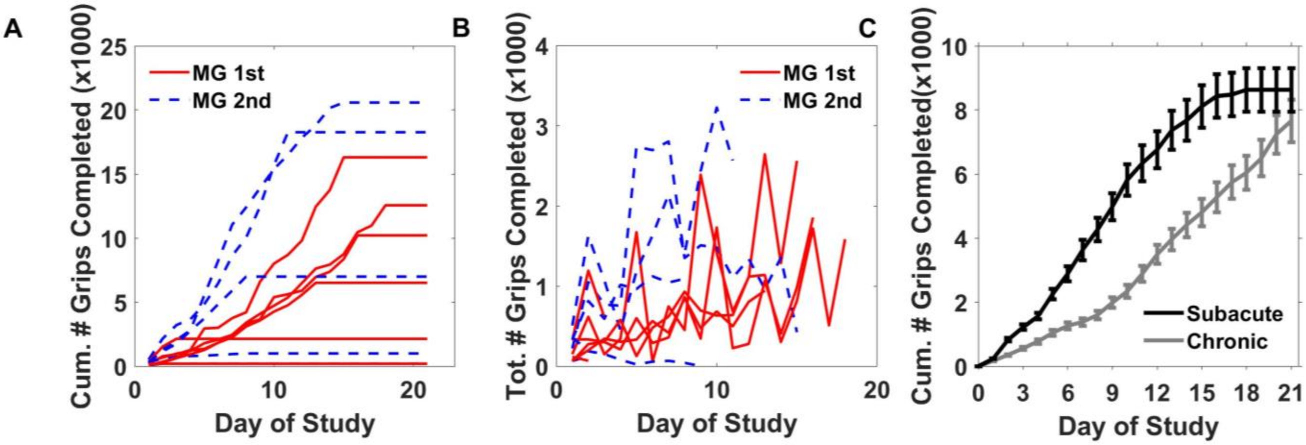

Figure 8. Summary of usership of the MusicGlove device. **A**) The cumulative number of grips completed by each subject in the group that received the MusicGlove first (MG 1st), and the group that used the MusicGlove second, after three weeks of conventional home therapy (MG 2nd). **B)** The total number of grips completed each day by each subject for both groups. **C)** The average cumulative number of grips completed by the subjects from the current study compared to number completed by chronic stroke survivors from a previous study [30]. Bars show ± 1 SE.

This number of grips was comparable to the amount in the previous study of individuals in the chronic phase after stroke (mean 6953 +/- 6546 SD, t-test, p = 0.8) (Figure 13C) [30]. In this previous study, subjects followed an identical protocol. In the present study, the MG 1st group had an initial BBT score of 21 +/- 14 (compared to 33.0 +/- 10.6 in the prior study), while the MG 2nd group had an initial BBT score of 33 +/- 15 (compared to 32.6 +/- 10.6 in the prior study).

We compared this level of compliance in total use time to other studies of technologies for home rehabilitation of the upper extremity that report individual usage data (Fig 9B) [79], [80].

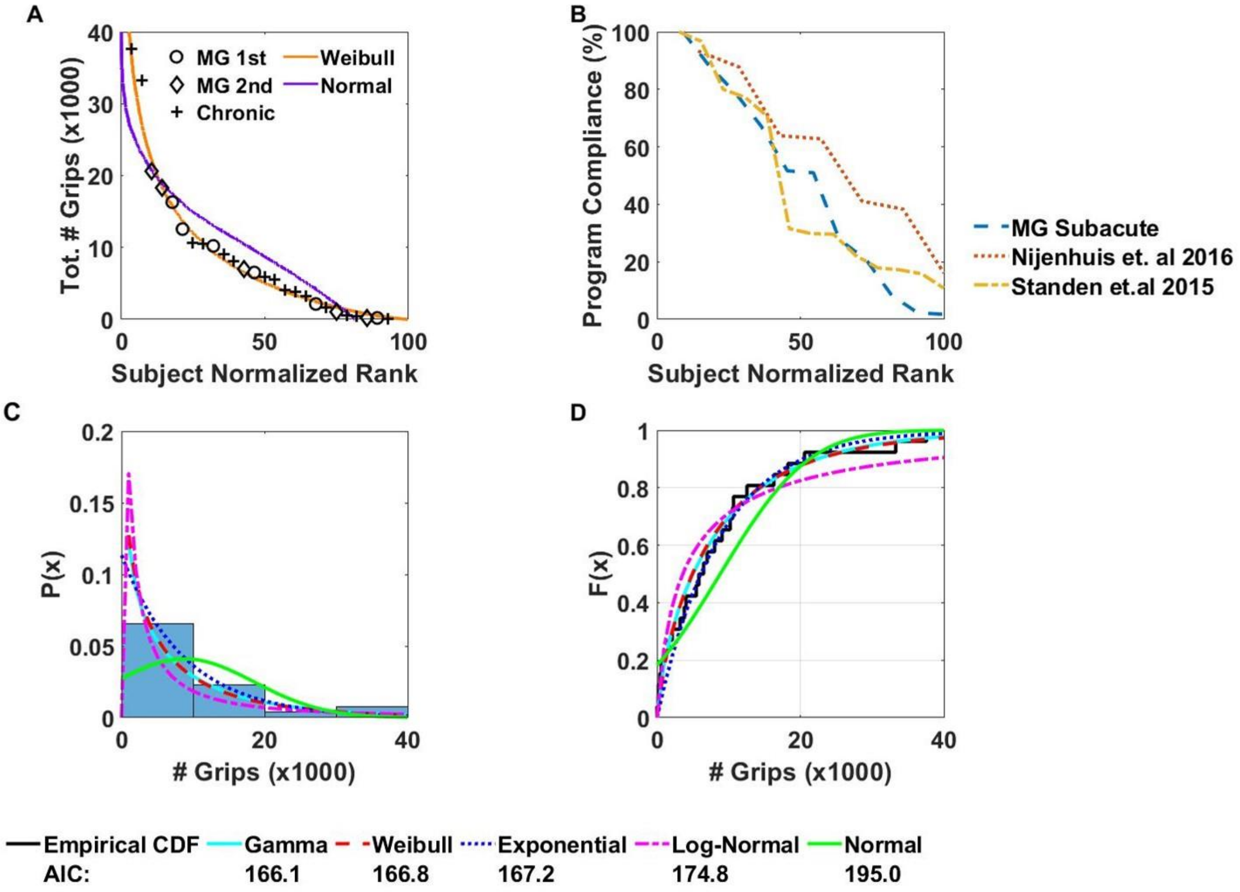

Figure 9. Analysis of underlying distribution of grip data, and user program compliance. **A)** The total number of grips completed versus the subject normalized rank (subject number / total number of subjects *100). Data from present and previous study with chronic users are combined. A Weibull distribution (shape parameter λ = 9400, scale parameter k = 0.96) fit the data well, better than a normal distribution **B)** Program compliance (# of hours device used / recommended hours of use) versus the subject normalized rank. Each line represents a different study which utilized a different home rehabilitation technology for the upper extremity **C)** Histogram of the total number of grips completed by all subjects against the probability distribution function estimate. Each distribution's probability distribution is also plotted over the histogram. **D)** Empirical cumulative distribution function plotted against the theoretical cumulative distribution function of various distributions.

Both studies were conducted with chronic stroke survivors with the time-after-stroke being 32.8 +/- 12.0 and 91.3-weeks post stroke respectively. However, in [36] the intervention was a virtual reality glove while in [37] the intervention was a hand orthosis combined with an arm support system. In terms of the level of impairment subjects in [36] had an average Wolf Motor Function Test score of 3.8 +/- 3.9. While subjects in [37] had an average Fugl-Meyer Assessment score of 37.0. Note that in [37] only averages were given, and standard deviations were not reported. For comparison the average Fugl-Meyer Assessment score was 44.3 +/- 12.6 for the MG 1st group, and 42.4 +/- 8.7 for the MG 2nd group. In these studies, the average compliance was 58% and 46%. Additionally, when program compliance was plotted against the subject normalized rank for each study, they both followed a similar pattern that decreased continuously (i.e. subjects could not be classified easily as high and low users).

The difference between subacute and chronic study populations in cumulative amount of practice at each day during the study was not statistically significant (Fig. 8C). However, the subacute user group in the present study did, on average, significantly decrease the number of grips during week 3 compared to week 1 (paired t-test, $p = .05$), a pattern different from the chronic users, who significantly increased the number of grips during week 3 compared to week 1 ($p = 0.008$).

When we rank-ordered the users in terms of number of grips (Fig. 9A), we found that subjects again could not be grouped easily into clusters of high and low users. Rather, the rank-order distribution decreased smoothly, similar to the distribution from the previous chronic study. This led us to consider what type of probability distribution can generate this data. We combined data from the subacute and chronic studies for this analysis since they were not significantly different at any day (Fig. 9C). We found that the Gamma, Weibull, and Exponential fit the data well (Fig. 9D). These are related distributions that arise due to failure dynamics of machines, a connection we will return to in the Discussion.

2.3.3. USAGE PATTERNS: CHALLENGE SELECTION

Subjects predominately played the game at song difficulty levels 1 and 2 and rarely at the most difficult level 3 (Fig. 10A). They most frequently used 1 or 5 grip types (Fig. 10A). Subjects changed parameters after 31% of the songs, favoring changing the number of grips over song difficulty (Fig. 10B). They achieved note-hitting success of greater than 75% for 84% of the 1061 songs played (Fig. 10C).

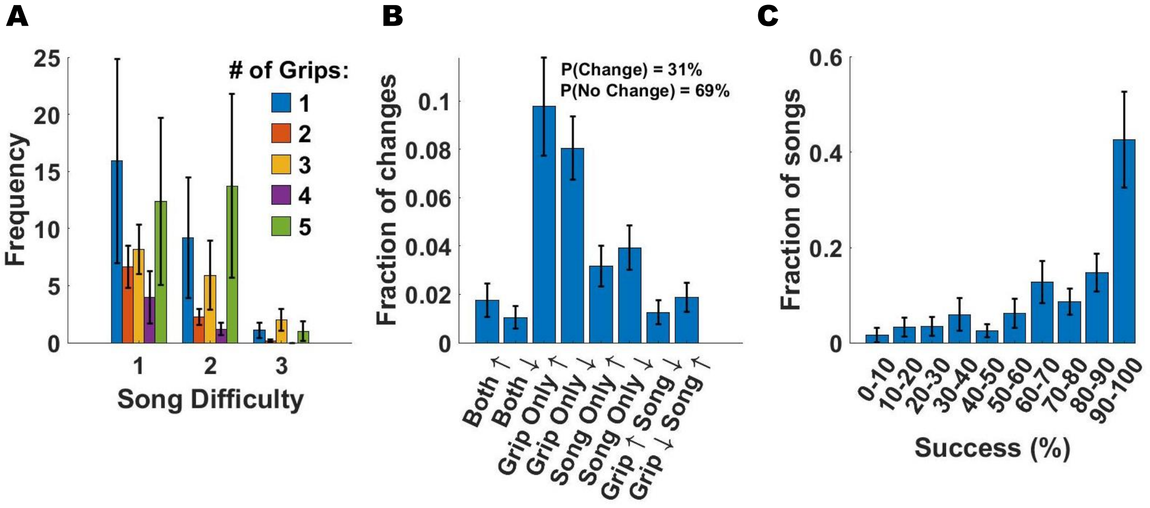

Figure 10. Analysis of adjustments made to game parameters across 1061 songs, as well as analysis of success levels. Each color on the plots A, B, D, E represents a different subject while each dot represents one song. **A)** Scatter plot of the song difficulty (1: easiest, 3: hardest) versus the number of grip types used **B)** Fraction of different types of parameter changes. The percent of games were a parameter was not changed was 69%. **C)** Fraction of songs played at different success levels.

The probability of subjects increasing difficulty of gameplay increased with success (linear regression, $R^2 = 0.32$, $p = 0.009$), and the probability of decreasing difficulty decreased with success ($R^2 = 0.85$, $p < 0.001$) (Fig. 11). The success level at which the probability of increasing and decreasing difficulty were equal was 74%. Even though the probability of increasing difficulty increased with higher success, note that there was still a finite chance that subjects decreased difficulty (~6% chance of decreasing difficulty at

90% success). The same pattern of randomness was true at low success levels (Fig. 11). When success was lower than 60% subjects were more likely to decrease the game difficulty (p = .05, two-tailed, paired t-test) while when success was higher than 80% subjects were more likely to increase game difficulty (p = .02).

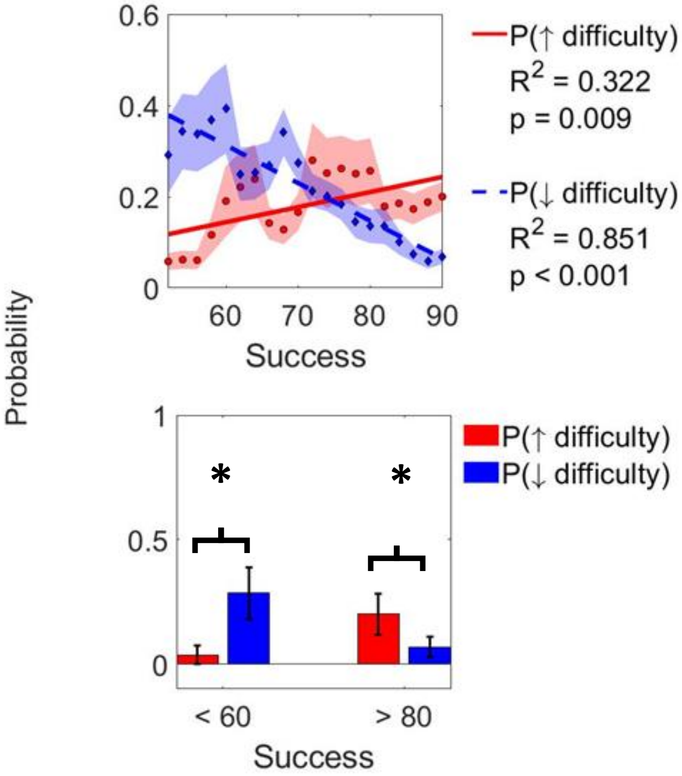

Figure 11. Top. Probability of increasing (solid line) or decreasing (dashed line) game difficulty (via song difficulty or number of grips) as a function of success on previous song. Each point is a probability calculated based on all songs played within 10 points of success level of that point. We required at least 100 songs to plot a point. Since subjects rarely played at low success levels, no points below 65% success were included. **Bottom**. Comparison of probabilities of increasing or decreasing game difficulty at low and high success. * denotes $p < 0.05$.

The amount of practice (measured by either the number of grips presented or total usage time) was not correlated with the average level of success experienced or initial impairment level, measured with the BBT. However, the amount of practice (measured as total # of grips presented Fig. 12A or total usage time, Fig 12B) was inversely correlated with the amount of parameter exploration (defined as the total number of parameter adjustments/total number of songs played).

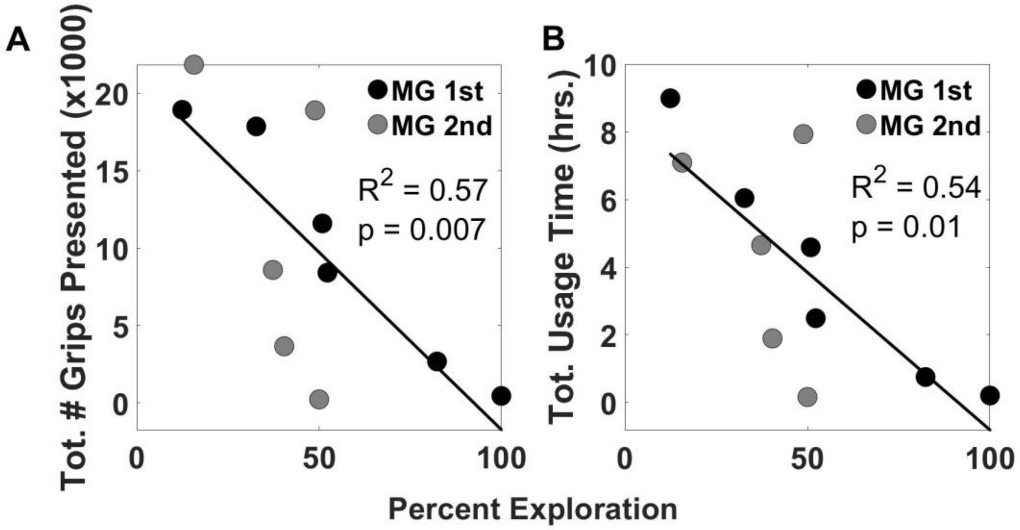

Figure 12. Amount of practice of each subject from both groups represented as both the total number of grips presented and the total usage time versus the percent exploration. Percent exploration is defined as the total number of song parameter adjustments / total number of sessions played.

2.3.4. PRELIMINARY ESTIMATE OF THE EFFECT OF MUSICGLOVE ON HAND FUNCTION

The average baseline BBT score prior to any intervention was 21 +/- 14 for the MG 1st group, and 33 +/- 15 for MG 2nd group (Fig. 13). The BBT score increased throughout the study. The MG 1st group had a greater average change in BBT score as compared to the MG 2nd group at all evaluations (e.g. 12 +/- 4 for MG 1st group vs 7 +/- 5 MG 2nd group at the end of the first phase of therapy). We did not perform a statistical analysis comparing groups because of the small sample size.

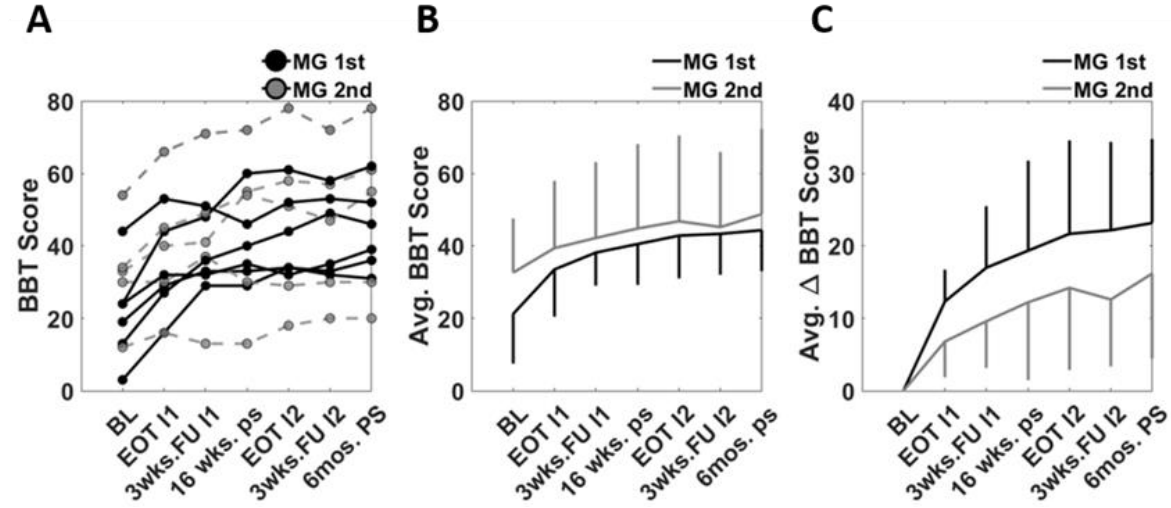

Figure 13. A) Individual trajectories of BBT score throughout the study. **B)** The average BBT scores for the two groups. Vertical lines represent one SD. **C)** The average change in BBT score relative to the baseline evaluation.

2.4. DISCUSSION

2.4.1. FEASIBILITY OF USING WEARABLE SENSING FOR FINGER REHABILITATION AT HOME EARLY AFTER STROKE

Like many wearable movement sensors for hand rehabilitation, the MusicGlove requires a moderate level of hand function to be used effectively as the user must engage the sensor for it to register that a movement has occurred. From our previous work we determined that individuals with a score of at least three on the BBT can reliably operate the device [47]. Here, we found that only ~13% of individuals 1-10 weeks post-stroke who met all other inclusion criteria also met this hand function criterion. Conversely, nearly 60% had too poor of hand function to participate. This observation indicates the importance of continuing to develop alternative hand training technologies, especially for people early after stroke when the brain is considered to be more receptive to rehabilitation.

One possible solution is to design sensors that allow more subtle movements to be detected. MusicGlove is limited by the use of contact sensing pads that require specific movements to be completed, and thus the features of “acceptable movements” cannot be varied. MusicGlove also only provides information about movement completion rather than real-time position data. A recent study that examined the percentage of subacute stroke subjects able to control mobile gaming technologies found that about 60% could use the paretic hand to control a cursor with a tablet or smartphone with swiping motions, and 93% could control a cursor with isometric grip force control [81]. Such interfaces, coupled with games, could help make home-based hand training more accessible to more people with stroke.

Another possible solution is to add actuation to the device to physically assist the user in making gripping movements. However, adding actuation doesn’t solve the problem that the user must still generate hand-related control signals to activate the assistance. Robotic assistance applied to a passive user has little therapeutic benefit [82]. Detecting movement-related signals at the level of the brain [83][84] or muscle [38], rather than relying on the resulting movement itself, is a possible solution, but increases complexity for home use because of the requirement to apply electrodes.

2.4.2. USERSHIP OF MUSICGLOVE: AMOUNT OF USE

For subacute subjects with adequate hand function, using the MusicGlove was feasible. On average, the subjects in the present study utilized the system to achieve a number of grips slightly greater than the number that was completed by chronic stroke survivors in the previous study. Thus, the life circumstances associated with the subacute phase of stroke did not limit engagement with this technology. However, on average, the subacute users significantly decreased their usage over time, a pattern different from chronic users.

Perhaps their ongoing spontaneous hand recovery contributed to more rapid abandonment. Alternately, they may have had relatively more untried therapy options available compared to chronic users, and abandoned MusicGlove in favor of exploring those options. One other possible explanation could that these are receiving standard-of care rehabilitation therapy and thus have an increased amount of medical appointments. This increased busy-ness could interfere with research procedures [85].

Despite achieving a relatively large number of grips on average (> 8000), user compliance was moderate (46%) in completing the requested hours of use. Few studies exist that were conducted in the home setting with subjects from the sub-acute stroke population that report individual usage data, making direct comparisons difficult. Although the other home-based studies compared in this manuscript (Fig. 9B) were conducted with subjects from the chronic stroke population, they provide a start for understanding compliance with upper extremity rehabilitation devices in the home setting. In the current study moderate user compliance may have arisen in part due to poorer motivation to use the device amongst users with higher hand function, although amount of practice was not correlated with initial or final BBT score. Continuing to understand the factors influencing compliance is an important direction for future work.

Some insight might be gained by considering the distribution of amount of practice. We found that the Gamma and Weibull distributions fit the data well in comparison to a Normal distribution. These related distributions are commonly used to model machine failure. For example, a Gamma distribution arises as a time-to-first-fail distribution for a redundant system. If there are n-1 backup units and all backup units have exponential lifetimes, then the total lifetime has a Gamma distribution [86]. The Weibull distribution characterizes the time to failure for many machines [87]. This is because machines are typically made of many parts, each of which can cause the machine to fail. When each part lasts a minimum time, but then fails probabilistically, Extreme Value Theory can be used to show that the Weibull distribution arises for weak conditions on the part failure probability distributions [87]. It may be possible to draw an analogy to understand usership patterns of home rehabilitation technology. For example, there are dozens of probabilistic factors (e.g. psychological, technological, sociological, cultural, neurologic) that can cause a person to stop practicing with a home-based rehabilitation technology, and each likely has a minimum time to “activate”. Thus, one would expect usage to follow a Weibull distribution. The fact that a Weibull distribution fit the data well then suggests usership may rely on a large number of subject specific factors. Exploring the use of machine failure theory and reliability analysis to gain insight into home usership is an interesting future research direction.

2.4.3. USERSHIP OF MUSICGLOVE: CHALLENGE SELECTION

The Challenge Point Hypothesis (CPH) from the motor learning literature posits that there is an optimal task difficulty for promoting skill development [88]. The CPH has been proposed to apply to rehabilitation as well [89]. In the context of movement recovery, rehabilitation therapists normally select an appropriate challenge level for each patient for each therapy task, consist with the CPH. A concern about self-administered care in the home setting is whether patients will challenge themselves enough during therapy. In the present study, we allowed the user to modify at will two parameters that affected the challenge of training. A key question was whether they would use this ability in a way consistent with the CPH.

We observed that the subjects tended to leave the parameters at a level that allowed them to play the game at high success levels (>75% success for 84% of songs), infrequently making changes to the parameters (on only 31% of songs), though higher difficulty settings were available. When they adjusted parameters, they did so in a way consistent with the CPH - tending to increase difficulty if their success at the last song was high, or decrease difficulty if success was low. The magnitude of these changes was low (14% increase across a change in success of 40%). These findings illustrates that 1) users tended to not make changes to difficulty; 2) when users did make a change they tended to do the logical thing (increasing difficulty when success is high, and decreasing difficulty when success is low); 3) user behavior was stochastic or explorative, as there was still a finite probability users did the “illogical” thing (increase difficulty when success was low).

Within the stroke rehabilitation technology literature there exist many examples of adaptive algorithms for adjusting task difficulty based on movement performance [90]. These algorithms often adapt task parameters to modulate the level of challenge experienced by the user after each sensed movement attempt. These types of algorithms are thought to be advantageous as they can be tuned to provide assistance matching an individual’s changing needs. However, we observed in the current study that people infrequently made changes to the game parameters. Further, subjects who exhibited less exploration (defined as total number of game adjustments / total number of songs played) used the system more. This suggests that if we are to make algorithms that more closely align with desirable human usership behavior, a less aggressive (i.e. not adapting as often) and more stochastic approach (i.e. sometimes adapting in the “wrong” direction) may be warranted.

We also recently found in a study of robotic finger training that training with a higher success level (80% - generated by robotic assistance) resulted in higher motivation and better long-term retention, particularly for more-impaired users [35]. The fact that the subjects in the present study preferred similarly high success levels, coupled with their CPH-consistent parameter adjustment behavior, suggests that persons with a stroke indeed have intuition about how best to practice.

An interesting possibility is to more rigorously characterize each home user as a stochastic decision process and analyze whether subject-specific decision rules predict greater usage or better therapeutic results. Such analyses will require larger data sets, which hopefully will become available with the growth of home-based commercial rehabilitation technologies.

2.4.4. LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Budgetary constraints coupled with the small percentage of people who could qualify for the study hindered our ability to recruit the planned number of subjects for the study (N = 20 for each group). The small sample size, plus the fact the MG 2nd group had a higher baseline BBT score, made it unfeasible to directly compare the therapeutic effect of MG 1st to MG 2nd in the first training phase. However, the data provide an initial estimate of effect size, which can be useful for planning future studies. The data were also suggestive that earlier access to the MG produced a larger change in BBT score. These findings support conducting larger efficacy studies to test whether MusicGlove or other movement sensors for hand training can facilitate quicker or larger recovery of fine motor function.

We asked subjects to log their conventional hand training, but they did not consistently do so. Thus, we could not make comparisons in compliance or analyze possible dose effects of the conventional training approach. The amount of difficulty adjustment we observed may have been influenced by the instructions and by how subjects interpreted them. The influence of pre-training on the way users use home rehabilitation technology is an interesting topic for future research. We pooled subjects from the MG 1st and MG 2nd groups for analysis. There may have been order effects, such as that subjects in the MG 2nd had a lower level of hand impairment when they started using the MusicGlove because of ongoing recovery. However, we found significant effects for the combined group even with this possible source of increased variance.

2.5. CONCLUSION

Only a small fraction of consecutively enrolled stroke patients could qualify for this study, having the appropriate level of hand function for using a wearable movement sensor-based rehabilitation approach, and meeting the other inclusion criteria. This suggests that further research needs to be done to develop devices that can help a larger proportion of people who have a severe hand impairment early after stroke. Among the population with the required amount of hand function, the sensor and musical game presented in this study were feasible for autonomous home use and caused no adverse effects. We found a possible connection between machine failure theory and usership via the form of the distribution of amount of use. We also observed that subjects played mostly at high success levels, infrequently making parameter changes when playing the game. When they did make changes, they did so in a way consistent with the Challenge Point Hypothesis, but with an element of randomness suggestive of exploration. These analyses point to the need to analyze “in-the-wild” user decisions in larger populations to understand how usage patterns might be associated with longer and/or more effective use of rehabilitation devices.

CHAPTER 3. RESIDUAL HAND MOTOR CONTROL IN INDIVIDUALS WITH CHRONIC STROKE: PRESERVATION OF FLEXOR CONTROL PERFORMANCE

3.1. INTRODUCTION

In the previous chapter we showed that only a fraction (~14%) of individuals in the subacute phase of stroke qualify for sensor based rehabilitation. This provides further evidence for the need of robotic devices that offer additional assistance to the user. However, one of the key challenges that needs to be addressed before robotic technologies will see widespread use in clinical, and home spaces is how best to provide intuitive and robust control. We hypothesize that to develop more intuitive and robust control strategies we first need to look at what aspects of motor control of the hand are compromised after stroke

Stroke remains one of the leading causes of chronic disability in the United States. After a stroke , approximately 80% of individuals experience impaired upper extremity function [91]. Hand-related impairments including spasticity, flexor hypertonicity, somatosensory loss, reduced muscle activation, and loss of finger individuation all play a role in reducing upper extremity function. Additionally, grip strength of the paretic hand ranges between 33%-50% when compared to the non-paretic hand [13], [15], [92][16], [93] [1], [14], [18], [94]–[96]. This constellation of impairments conspires to reduce task performance speed and accuracy and increases the time necessary to complete functional assessments [4].

It is also common after stroke for individuals to experience deficits in force control. Broadly, force control is defined as the capability to generate accurate and steady force output that matches a target goal including timing of muscular force production. There have been several force control studies that have examined how force control is impacted after stroke, and have found that force production magnitude and variability between the paretic hand and non-paretic hand are asymmetrical, patients exhibit greater force variability during both unimanual and bimanual isometric force control tasks, and there is an increase in task performance error during isometric force control tasks [97]–[102].

However, although there have been studies that have shown deficits in grip force control recent clinical observations, as well as recent quantitative studies, suggest that at appropriate force levels finger motor control is somewhat preserved after stroke. For example, Lindberg et al. recently showed that isometric grip force control is relatively well preserved at low grip force levels [103]. In that study 24 chronic stroke were instructed to follow target force trajectories with a cursor as precisely as possible with subjects grip force controlling the cursor. The force tracking task was comprised of 6 blocks, each consisting of 4 ramp-hold-and-release target force trajectories at force levels that varied between . In comparison to controls, the chronic stroke subjects had increased error, force variability and release duration. However, at similar absolute force levels there was not a significant difference in tracking error or variability [104]. This suggests that stroke patients preserve the ability to modulate power grip force within a limited force range.

In another study, 17 persons in the chronic phase after a stroke played a grip force tracking game. Participants squeezed a force transducer using a power grasp to move a cursor into a target at different force levels, defined to be 3 to 30 % of their maximum voluntary contraction (MVC) [105], [106]. Participants with Box and Block test (BBT) scores as low as 3 could regularly acquire the target, with a minimal increase in task completion time (~ 1 second increase). Additionally, their acquisition times did not depend strongly on their BBT score .

Both of the previously mentioned studies thus provide evidence that persons with stroke have a relatively masked ability to sufficiently control isometric finger flexion forces. Further this raises the question of how does this isometric force control ability compare to other measures of hand function after stroke such as finger dexterity, and grip strength? In the present study we sought to answer this question by calculating a ratio between impaired hand function score to unimpaired hand function score and comparing this measure for three different categories of hand function: dexterity, grip strength, force control.

Many studies have focused on grip force control after stroke using either a power grip or the index finger. A power grip primarily relies on flexion of the fingers to exert force on an object resting against the soft tissue between the index finger and thumb; the thumb provides some support but does not contribute greatly to force production. Furthermore, one could argue that previous studies have demonstrated the force control ability of the fingers but not necessarily the thumb. There exist very few studies that have examined force control in the thumb [92], [107], [108]**.** This comes as a surprise given the thumbs critical role in the completion of other grip types such as a cylindrical grip, or a lateral pinch grip, two grips that we use often in daily living [39]–[41], [109]. Therefore, another question of interest was how does this isometric force control performance compare between the fingers and the thumb?

3.2. STUDY PARTICIPANTS

Twenty individuals with a chronic stroke were recruited to participate in this pilot study. Inclusion criteria were: ischemic or hemorrhagic stroke at least 6 months post-stroke, moderate to severe weakness of their affected upper extremities, define as a score > 0 on the Box and Blocks Test. Exclusion criteria were significant pain of the affected upper extremity, severe loss of sensation of the affected upper extremity, concurrent severe medical problems, cognitive dysfunction to an extent that would interfere with participation, visual deficits, and severe neglect or apraxia. All subjects gave their informed consent before participation in the study, and this study was approved by the Institutional Review Board of the University of California, Irvine.

3.3. OUTCOME MEASURES

3.3.1. CLINICAL ASSESSMENTS OF HAND FUNCTION

Hand function was evaluated using two standardized functional measures: The Box & Block Test (BBT) and the Nine Hole Peg Test (NHPT). The BBT evaluates unilateral gross manual dexterity by observing how many small blocks a subject can pick up and place from one side of a box to the other in 60 seconds [77]. The NHPT evaluates finger dexterity by requiring subjects to take pegs from a container, one by one, and place them into the holes on a board. Afterwards subjects must remove the pegs from the holes, one by one, and replace them back into the container as quickly as possible [110].

3.3.2. MAXIMUM VOLUNTARY CONTRACTION (MVC)

Participants were asked to squeeze a force transducer using each of the two different grip types specified in the study (lateral pinch grip or power grip) as hard as they could for four seconds without any visual feedback. Afterwards participants were given four more seconds to rest. This rest period was followed by an additional grasp attempt that was also four seconds in length. During this second trial participants received visual feedback in the form of a red dot on the computer screen that moved higher up a vertical bar the harder subjects squeezed (Fig.14). The scale of the visual feedback was set such that the average force produced during the first attempt corresponded to the middle of the bar during the second MVC attempt. The peak of the second attempt was taken as the participant's MVC. This was done for both the unimpaired and impaired hands of each participant.

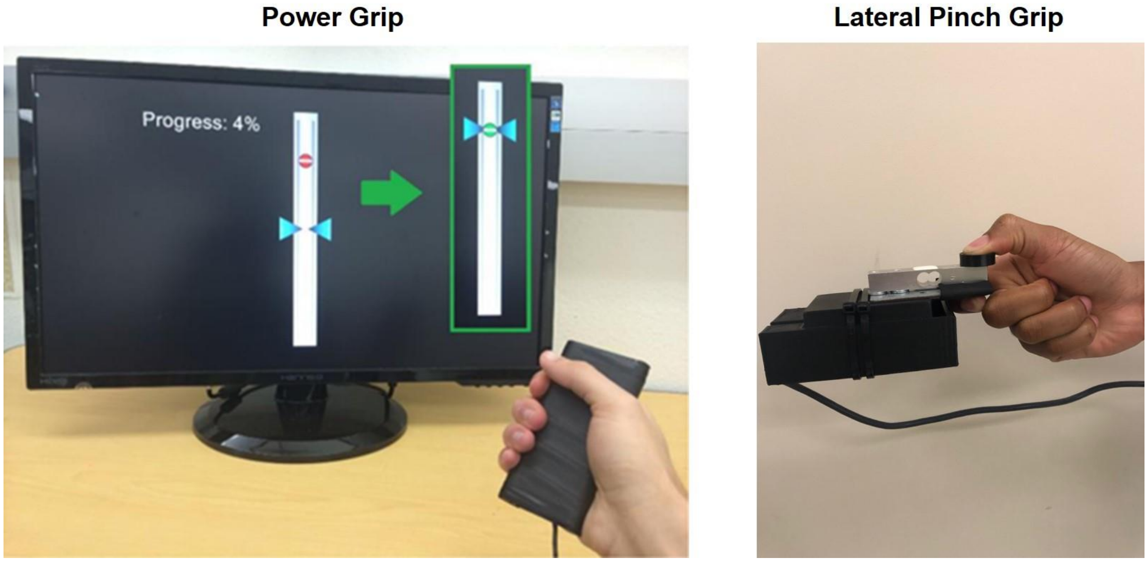

Figure 14. Two different grip types were used during the study to complete the grip force tracking game; a power grip **(Left)**, and the lateral pinch grip **(Right)**

3.3.3. ISOMETRIC FORCE CONTROL

Isometric force control was evaluated using a grip force tracking game implemented in a previous study [105] using the two different grip types specified in this study. Participants were asked to squeeze a force transducer to move a cursor to track a circular target. There were eight different target levels that corresponded with eight evenly spaced force levels between 3% and 30% MVC. The vertical position of the cursor on the display was proportional to the participant's grip force. The target changed colors from red to green whenever the cursor was inside a window around the target (this window was not visible). The size of this window was made large enough so that it required little practice from the participants to remain in the target window. This was achieved by increasing the width of the window quadratically with force: 1.50%, 1.51%, 1.59%, 1.79%, 2.08%, 2.42%, 2.78% and 3.14% MVC for the eight targets in ascending order [105], [106]. There was a total of 96 trials. On each trial the target remained fixed at the current force level until the participant moved the cursor the target window for 0.3 seconds. When that was achieved, the participant was required to keep the cursor in the window for 1.5 seconds to trigger presentation of the next target. After this 1.5s block, the target moved to a new position and a new trial began. Subjects had a maximum of 8.5s to reach the target before it moved to another position on the screen. The grip force tracking task was completed with both the impaired and unimpaired hand of the subject.

3.4. EXPERIMENTAL PROCEDURE

Subjects who met all inclusion criteria were enrolled in the study and proceeded to assessment one. During this first assessment baseline measures for all clinical assessments were taken. Afterwards, subjects MVC with the lateral pinch grip and power grasp were obtained. Afterwards subjects played the grip force tracking game using the same grips they used to perform the MVC test. The order in which subjects performed the tasks were randomized using a Williams Design Latin Square to minimize first order carry over effects.

3.5. DATA ANALYSIS

We defined tracking time as how long it took participants to acquire and remain inside each new target, measured from the time when the target was presented to when the target was entered. Tracking time increases as impairment increases; in contrast, grip strength and the clinical hand function measures decrease as impairment increases. Therefore, to be able to compare impairment levels for all scales, we converted tracking time into the effective target acquisition frequency, defined as 1 over the tracking time. Target acquisition frequency can be interpreted as the frequency as which participants would acquire targets sequentially presented; it decreases as impairment increases. Going forward, we will use the term “flexor control” to refer to the target acquisition frequency metric.

To compare the relative preservation of the various outcome measures, we calculated impairment ratios for each measure, defined as the score received on the assessment with the ipselisonal hand divided by the scored received using the contralesional hand. The impairment ratio reflects normalization to the functional ability of this hand, rather than normalization to what is a normal score, since the ipsilesional hand often shows some decreased ability [3,4]. We calculated this ratio for the BBT, NHPT, MVC, and flexor control scores. We performed a repeated-measures analysis of variance on these impairment ratios. We followed up this analysis with pairwise t-tests using Bonferroni’s correction method. We used Spearman’s Correlation coefficient test to evaluate the relationship between BBT scores and IFC frequencies for both the power grip and the lateral pinch grip. We performed all statistical analysis sing the R programming software.

3.6. RESULTS

There was a statistically significant difference between the measures of function, grip strength, and force control (3.96,71.22) = 9.5, $p < .005$, Repeated Measures ANOVA). Follow-up analysis using pairwise t-test with Bonferroni's correction method revealed that the impairment ratios isometric force control were significantly greater than the impairment ratios for the dexterity and grip strength measures when using the power grip ($p < .001$, $p < .001$ respectively). A similar trend was seen when participants were using a lateral pinch grip, with the impairment ratios for isometric force control being significantly greater than the impairment ratios for dexterity ($p < .01$). However, there was not a statistically significant difference between isometric force control and grip strength with the lateral pinch grip. Additionally, no other comparisons were statistically significant (Fig.15).

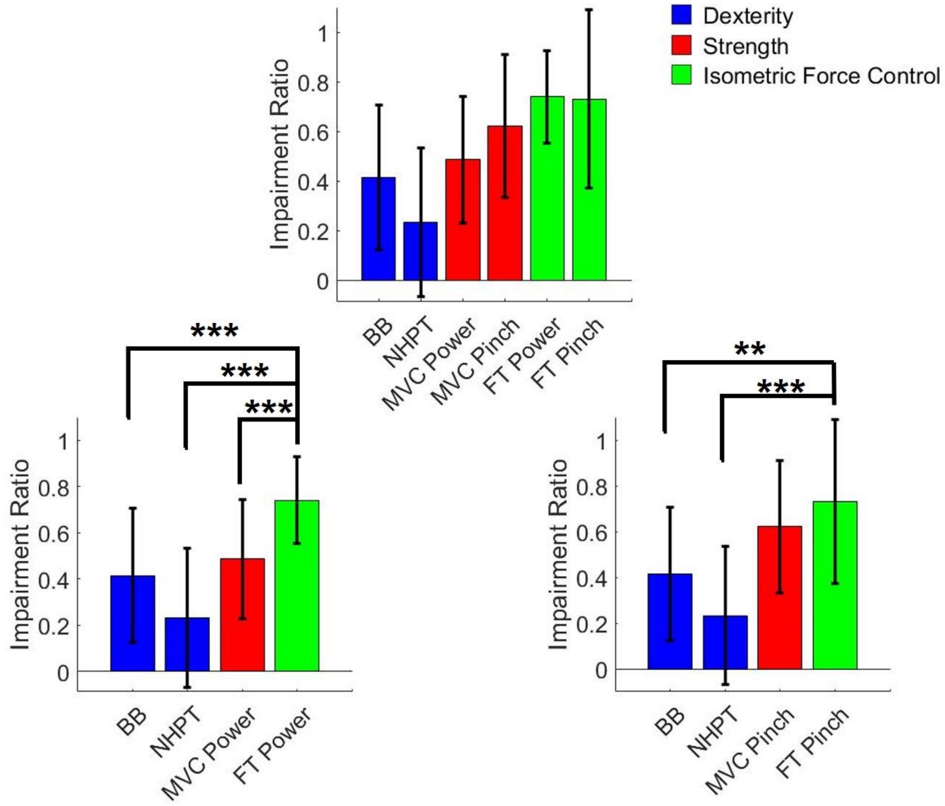

Figure 15. Top) Impairment ratio for clinical assessments, MVC testing, and the tracking time. **Bottom)** In this plot the impairment ratios for strength and isometric force control (IFC) are separated by grip type with the bottom left being a power grip and the bottom right being a pinch grip. For both plots each bar represents the average across all subjects, and here the impairment ratio is the score received using the impaired hand divided by the score received using the unimpaired hand. * denotes less than .05, ** denotes less than .01 and *** denotes less than .001.

There was no correlation between BBT scores and IFC frequencies for both the power grip and the lateral pinch grip (p = 0.28, p = 0.97, respectively). Further when the impairment ratios for IFC are plotted against BBT scores majority of subjects possess impairment ratios greater than .5 for both grip types. This is also true for subjects who have relatively low BBT scores (Fig.16).

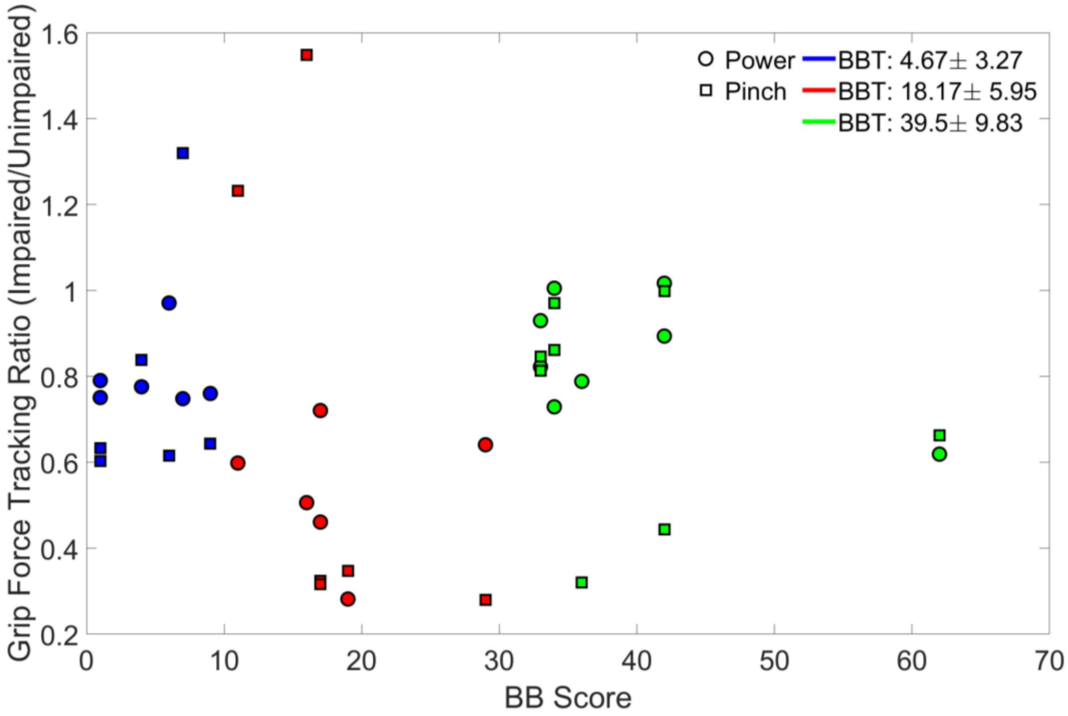

Figure 16. Isometric grip force tracking impairment ratio vs. Box and Block test score. The isometric grip force tracking impairment ratio represents the impaired tracking frequency divided by the unimpaired tracking frequency. For the Box and Blocks test score subjects were stratified into three different groups; subjects with Box and Block scores ≤ 10 (blue), subjects with scores between 10 and 30 (red), and subjects with scores greater than 30 (green). The average Box and Block scores are shown with each of these groups along with standard deviations. Two different marker types are used to distinguish the two different grips used to perform the grip force tracking task.

3.9. DISCUSSION

3.9.1. UNDERSTANDING NEURAL CONTROL MECHANISMS AFTER STROKE

Persons with stroke retain the ability to modulate their grip force at low force levels. When this ability is compared to dexterity or grip strength after stroke, flexor control is significantly less impaired. This raises the question then of why is flexor control preserved after stroke in comparison to other aspects of hand function such as dexterity or grip strength. Insights from the field of neuroscience may further our understanding and provide clarity as to why some aspects of hand function are spared as compared to others after stroke. The current body of knowledge suggest that after a stroke depending on the functional integrity of the cortical spinal tract (CST) motor regions shift from primary to secondary motor networks to generate motor output to spinal cord motor neurons [102], [111]. Specifically, recent studies have shown that the motor system recruits the contralesional cortico-reticulospinal tract [CRST] which can access the reticulospinal tract [RST] through the contralesional premotor cortex and supplementary motor area. The reticulospinal tract [RST] has also been shown to enable persons with a stroke to make gross finger flexion movements [112], [113]. Thus, reliance on the RST may serve as a back-up system after damage to the CST, and allow for gross movement, while also preserving some aspects of grip force control.

Preserved force control was not only seen in the fingers but also appeared to be equally preserved in the thumb as well. This raises yet another question of interest as to why this is the case. There is a great reliance of the thumb on the intrinsic muscles of the hand for dexterity and force production [92], [114]. The intrinsic muscles of the hand receive a substantial amount of input from the corticospinal pathways however, there is some evidence that would suggest that the RST synapses to the intrinsic muscles in the hand as well [112], [113]. Thus, the aspects of grip force control that we see in the thumb may also be preserved as a result of individuals relying more on the RST as well.

3.9.2. IMPLICATIONS OF PRESERVED FLEXOR CONTROL FOR REHABILITATION THERAPY

It is well known that there are impairments to grip force control after stroke such as decrease in maximal force produced by the paretic hands, impaired task performance (e.g., higher task error and force variability, and less coordinated forces between hands. However, here we have shown that at the appropriate force levels there are aspects of grip force control (flexor control) that are relatively well preserved. This observation presents an intriguing question: should rehabilitation efforts of the hand focus on rehabilitating grip force control since there are aspects of it that are preserved or should the focus be on aspects of hand function that are missing such grip strength or extensor control. One argument for focusing on other aspects of hand function instead of grip force control would be that working on grip force control could reinforce the reticulospinal pathway which could limit recovery. As it has been shown that individuals who shifted from using the RST to the CST are the ones who showed greater responsiveness to robot-assisted movement training, and greater improvement in motor function. Thus working on extension movements or other aspects of hand function that are missing might that engage the CST more may be more advantageous to improve overall hand function. However, recent work by Lodha [115] would suggest that working on grip force control could improve an individual’s ability to perform tasks that require fine motor control. In that study fifteen participants with stroke (upper-limb Fugl-Meyer score ≥43/66) and 15 controls performed the Nine-hole peg test, MVC testing, and a dynamic force tracking task with isometric finger flexion using the paretic and non-dominant hands respectively. The time to complete the nine hole peg task in the experimental group was primarily explained by finger force variability. Thus the ability to modulate forces contributes to fine motor dexterity, and developing interventions that focus on the preserved aspect of grip force control and continue to rehabilitate it could also potentially improve fine motor dexterity .

3.9.3. IMPLICATIONS OF PRESERVED FLEXOR CONTROL FOR ASSISTIVE TECHNOLOGY DESIGN

In the present study we observed that although dexterity, and strength may be severely impaired, isometric force control is well preserved in comparison. This preserved isometric flexion force ability represents a potential source of high-fidelity force control and could have implications in how we design rehabilitation technology. For example, a recent study published by Rinne [81] evaluated different control strategies to use in conjunction with mobile tablets for rehabilitation. It was found that using an adapted hand grip enabled directed control in 75% of the subjects and enabled full-range movement of the cursor on the tablet screen in 93% of the subjects. It should also be noted that the use of this grip control method enabled more severely impaired subjects to control the software in comparison to other methods tested. Outside of the potential use of this preserved isometric force control in gaming technology it could also have implications on the design of hand exoskeletons, specifically the control strategies that are implemented.

As it stands it remains a challenge how best to provide intuitive and robust control of a hand exoskeleton. A recent review published by Bos [38] indicated over 136 hand exoskeletons. In this review the list of control strategies was primarily dominated by the use of surface electromyography (sEMG) or the activation of a switch. However using a switch requires using the non-affected hand to trigger the movement which is not that intuitive, and although there has been some level of success with the implementation of

EMG as a control signal it still can be affected by electrode placement, and artifacts within the signal such as those cause by hair on the skin, or sweat. Other forms of intent recognition include Mechanomyogram which uses an accelerometer to record the frequency and amplitude of muscle vibrations. However, this can be affected by limb movement artifacts and has not seen much use in the exoskeleton space. Additionally, there has been some work done examining the use of force myography which uses the force changes on the surface of the skin during muscle contraction as a control signal. However, this method is still in the experimental phase although some researchers have looked to use it as a control source for upper limb prosthesis [116], [117]. Electroencephalogram (EEG) has also seen somewhat limited use in the hand exoskeleton space as in the previous mentioned systemic review of hand exoskeleton devices by Bos [38] over 136 devices where identified and 9 of those devices used brain activity measured by EEG cap as a control signal. This could be because it often requires intense interpretation to determine what areas are activated by a particular response.

One solution that we suggest based off the observations from the current study would be to mount a force sensor in the palm of the hand and measure the isometric grip force exerted by the fingers. Then use this force to control an exoskeleton that would facilitate a grip. Likely this grip would have to be either a pinch grip or two-finger chuck grip. One of the benefits of using such a strategy would be that movement of the impaired hand is triggered by the impaired limb which we believe will be more intuitive. This strategy also takes advantage of the abnormal flexural synergy that is present after stroke [118]–[120] which again would suggest that this may be very intuitive if not automatic for users. It was also shown that thumb isometric force control is also well preserved in addition to finger isometric force control. Therefore, another possible approach for a control strategy for a hand exoskeleton. One could design the hand exoskeleton using the thumb to control the exoskeleton, and have the exoskeleton facilitate a power grasp. It is important to note however that the force exerted by the user must remain low (between 10-30% MVC). Outside of this range isometric grip force control can be highly variable[104].

3.10. CONCLUSION

In comparison to manual dexterity and grip strength isometric grip force control remains relatively preserved after stroke in both the fingers, and the thumb. This preservation of grip force control could be due to the body shifting and using the reticulospinal tract given the damage that likely has been done to the corticospinal tract. This result warrants further research into possibly using this ability as a control source for exoskeletons or in the development of other rehabilitation devices.

CHAPTER 4. STROKE IMPAIRS POSITION AND TOUCH SENSING IN THE FINGERS INDEPENDENTLY, AND POSITION SENSING IMPAIRMENT IMPACTS HAND FUNCTION MORE THAN TOUCH SENSING

4.1. INTRODUCTION

In Chapter 3 we revealed that individuals with stroke preserve the ability to control isometric grip force, and discuss the implications that this preserved ability has on the design of control strategies for exoskeleton devices. However, although much of the focus of robotic technologies is placed on improving motor control, it is common for individuals to experience sensory deficits after stroke as well. One review found that the incidence of somatosensory deficits in stroke patients varied between 25% - 85%, depending on the method used to quantify the deficit and the particular aspect of somatosensation studied [8]. Another review reported prevalence in the range of 50% - 80% [121]. Studies focused just on proprioception found that the prevalence of proprioceptive impairments in upper extremity of stroke patients ranged from 17% - 60% [5]–[7], [122].

The prevalence of somatosensory deficit would be expected to affect motor function, as is well acknowledged that sensory feedback plays a vital role in the execution and learning of motor of tasks. This was, for example, made especially apparent in a series of studies conducted with persons who had neuropathy of the large diameter sensory afferents associated with position, velocity, and force sensing, but who still had intact motor systems. These subjects had impaired reaching accuracy and were unable to perform fine motor tasks [123], [124]. Proprioceptive deficits have also been shown to play a role in motor learning as in another striking experiment, monkeys who had the their primary somatosensory cortex laterally removed were no longer able to learn new motor tasks [125]. Proprioception impairment also was one of the strongest predictors of responsiveness in one of the largest trials to identify an effective upper extremity rehabilitation therapies - the EXCITE clinical trial of constraint-induced therapy [126]. Additionally, proprioception after stroke was recently shown to predict responsiveness to robot-assisted finger training [35].

While studies have shown the importance of sensory feedback to manual task execution and learning [123], [124], [127]–[130], the association between somatosensory deficits and motor function after stroke is still not well understood. Some studies have reported significant correlations indicating reduced motor function with proprioception deficit, while other studies have not. For example, a study of 102 chronic stroke survivors found that sensory impairments were related to mobility (Rivermead Mobility Index), and independence in activities of daily living (Barthel Index). Similarly, Rand et al. also reported that proprioception deficits of individuals with chronic stroke were negatively associated with upper extremity motor (Fugl-Meyer Motor Assessment) and functional abilities (Action Research Arm Test, Box and Blocks Test) and independence in daily living (Functional Independence Measure, IADL questionnaire) [131]. But in contrast to Rand and Tyson, 58 studies that examined upper limb recovery after stroke were recently reviewed in a meta-analysis conducted by Coupar et al. Among those studies, only baseline upper limb functional and impairment measures and neurophysiological factors (motor-evoked potentials and somatosensory-evoked potentials) were consistently identified as being strongly associated with upper limb recovery following stroke [132]. In a similar fashion, Katrak et al. also showed that sensory and proprioceptive function were not correlated with recovery of hand movement or function [133]. This disagreement makes understanding the relationship challenging and might be attributable to the nature of the clinical assessments typically used to evaluate somatosensory deficits.

The most common ways used in clinical practice to evaluate somatosensory deficits include the Fugl-Meyer Sensory scale: assess light touch and proprioception in pre-defined body regions and is comprised of a three-step scale for both light touch, and proprioception [134], the Thumb Localization test: The participant's affected arm is moved by the examiner to four different locations in space and each time, the participant is requested to find and grasp their affected thumb with their less-affected hand while their eyes are closed [135], the Rivermead Assessment of Somatosensory Perception: comprised of 8 tests which assess 6 sensations (sharp/dull discrimination, surface pressure, tactile localization, temperature discrimination, joint movement and joint movement direction discrimination) and 2 secondary sensations (sensory extinction and two-point discrimination) using a Neurometer [136], the Nottingham Sensory Assessment: a quantitative test performed bilaterally at the face, upper and lower limb that assess tactile sensation, kinesthesia, and stereognosis using standardized equipment [137], and the Quantitative Sensory test: a test that is comprised of 13 subtests that provide information about thermal detection and pain threshold, mechanical detection threshold for touch and vibration, mechanical pain sensitivity, allodynia, and tests for central processes such as pain summation to repetitive stimulus using a standardized test kit [138]. These tests are simple to administer but suffer from limitations such as poor inter-rater reliability, floor and ceiling effects, and limited resolution due the use of ordinal scales [8], [139], [140]. The limitations of these exams have led to the development of robotic devices that can assess somatosensory deficits after stroke. Robotic devices can objectively and reliably quantify attributes of sensorimotor behavior, and have a higher degree of sensitivity as compared to the standard clinical assessments [122], [140]–[143]. The development of these robotic devices has led to new measures of somatosensory deficits after stroke, which allows us to raise several key questions in a more quantitative way than has previously been possible.

First, is there a correlation between proprioceptive and tactile deficits after stroke? Many of the studies reviewed above consider proprioception and tactile deficits as manifestations of “somatosensory loss” in general. If the relative loss of proprioception and tactile deficits differs across persons with a stroke, this may account for some of the differing statistics on incidence of somatosensory deficit. Individuals may experience a variety of tactile deficits after stroke such as impaired tactile discrimination, tactile localization deficits, and impaired stereognosis, each which may be associated with damage in different brain areas [6]–[8]. Further, proprioceptive information and tactile information are processed in separate, though related, brain regions [140]. This would suggest that the two might be expected to be correlated with one another when a stroke affects the neighboring neural substrates responsible for both, but not to be correlated when a stroke is more locally focused. Further, for the hand, the relationship between proprioception and tactile sensation is complex. Our hands are covered with cutaneous mechanoreceptors that provide information in response to mechanical stimulation of the skin. Cutaneous information improves the perception of finger movement – i.e. proprioception [144]. Additionally, when cutaneous information is blocked it appears that the ability to detect movement suffers, but only for the hand as opposed to other limbs. Specifically, it becomes challenging to detect movement of the fingers [145], [146], but detecting movement of other areas of the body such as the knee remains intact [147], [148]. This suggests that while tactile information might not play a role in enhancing proprioception of other limbs, for the hand, it augments proprioceptive function. Thus, further investigation into the extent to which these two somatosensory modalities are related for the hand is warranted.

Second, what are the relationships, specifically for the fingers, between (on the sensory side) position and touch sensing, and (on the motor side) strength and manual function? Although there have now been many robotic devices developed to assess proprioception, most focus on the arm or the wrist. There have been few attempts to quantitatively and precisely measure proprioceptive deficits of the fingers, which is surprising given how often we use our hands to interact with objects, in addition to the fact that there are a substantial amount of cortical resources that are dedicated to the hand.

4.2. METHODS

4.2.1. STUDY PARTICIPANTS

Twenty individuals with a chronic stroke were recruited to participate this study. Inclusion criteria are shown in Table II. All subjects gave their informed consent before participation in the study, and this study protocol was approved by the Institutional Review Board of the University of California, Irvine.

Table II

INCLUSION CRITERIA

Ischemic or hemorrhagic stroke at least 6 months post-stroke
Moderate to severe weakness of subjects affected upper extremity but with residual function of the thumb
Absence of significant pain in the affected upper extremity
Absence of severe loss of sensation of the affected upper extremity
Absence of concurrent severe medical problems
Absence of cognitive dysfunction to an extent that would interfere with therapy participation
Absence of visual deficits
Absence of severe neglect or apraxia
Absence of severe spasticity or contractures at the affected upper extremity (score <4 on the Modified Ashworth Scale)

4.2.2. OUTCOME MEASURES

4.2.2.1. ASSESSMENT OF FINGER STRENGTH AND HAND FUNCTION

We determined individual’s maximum voluntary contraction (MVC) of power hand grip using the same protocol implemented in previous studies conducted in our lab [105]. We assessed hand function using the Box and Blocks test (BBT) and the Motor Activity Log (MAL). The BBT is a widely-used clinical assessment in which individuals try to move as many blocks as they can from one side of a box to another in 60 seconds [77], [149]. The MAL consists of a list of questions about the amount of use (AoU) of the impaired hand during functional activities, as well as the quality of their movement (QoM) during these activities. For each subscale the range of scores that can be given is between 0 and 5 with participants having the option of giving half scores as well (i.e., 0.5,1.5,2.5,etc.) [150], [151]. For both scales a 0 means that the impaired arm was not used at all to complete the given activity, while a 5 means that the ability of the individual to use their impaired arm is comparable to before they suffered a stroke (normal).

4.2.2.2. FINGER PROPRIOCEPTION ASSESSMENT

To assess finger proprioception, we used a robotic method we previously developed, called the “crisscross method” [142] (Fig.17). We placed one hand into the FINGER exoskeleton and positioned in front of the other hand a keyboard either on their lap or in front of them on a desk.

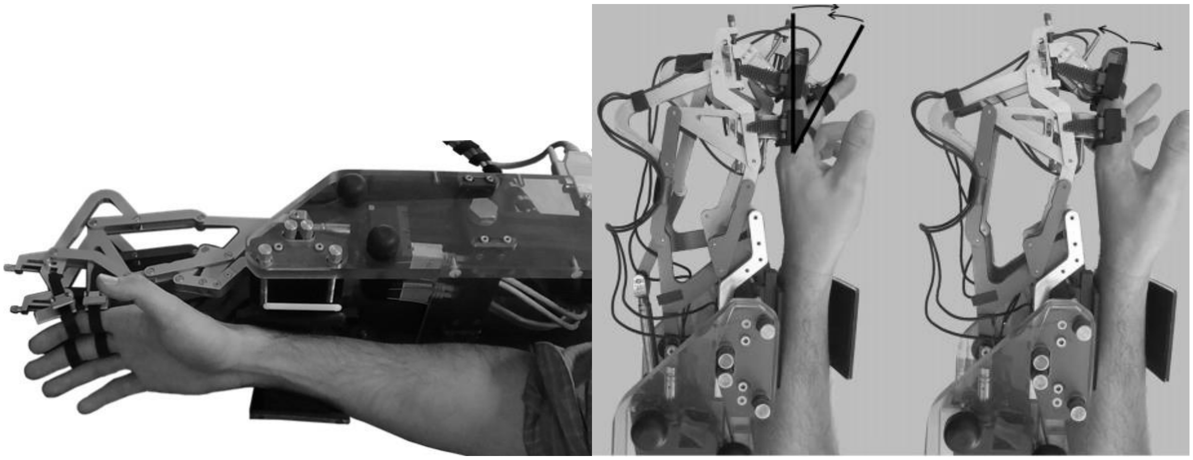

Figure 17. Left) Lateral view of the FINGER exoskeleton **Right)** A top view of the finger exoskeleton. The motion in which the FINGER exoskeleton moves the middle and index finger is also shown.

For the crisscross task, a task we created and validated earlier [142], the FINGER robot slowly moved the index and middle fingers past each other in a random pattern. We instructed subjects to press the spacebar on the keyboard with their unimpaired hand when they felt their index and middle fingers on their impaired hand overlap. Subjects experience a total of 12 crossing movements over a two minute period. Participants first performed two movements of the finger overlap task with their unimpaired hand to familiarize themselves with the task. Then they performed the complete 12-trial movement detection task with their unimpaired hand first, followed by their impaired hand. Both tests were performed without vision and subjects wore noise-cancelling headphones.

We defined the finger proprioception sensing error as the magnitude of finger separation, measured in degrees about the metacarpophalangeal (MCP) joint, which existed when the participant indicated they felt their index and middle fingers were directly overlapped. We averaged this error over the 12 trials for each subject.

4.2.2.3. TACTILE DETECTION TASK

We delivered the tactile stimulus using a vibration game developed on a smart phone (Fig. 18). Subjects placed their hands in a hand-wrist brace in front of the cell phone, which was held in a stand (Fig. 18). We helped subjects to adjust the position of the phone so that they could comfortably reach the screen with their thumb. To play the game subjects were required to place their thumb in the middle of the screen and wait until they felt a vibration. When they sensed a vibration they were instructed to press down on the screen with their thumb until they no longer felt the vibration. There were three different vibration durations: 50 ms, 1000 ms, and 2000 ms. Each subject experienced each of the three different types of vibration patterns three times. Subjects were given one test trial to learn the mechanics of the game followed by a trial for which we acquired data. The test trial consisted of subjects experiencing one vibration duration three times. Subjects performed the task with the unimpaired hand first followed by the impaired hand. For each vibration duration, we calculated a tactile acuity score as the number of times the subject responded to the vibration stimuli divided by the number of times the vibration was presented.

Figure 18. Left) smartphone game screen. Subjects were instructed to place their thumb in the center position of the phone indicated by the blue circle. Once subjects felt a vibration they squeeze on the circle in the center of the screen until they no longer felt a vibration. **Right)** Hand Wrist Brace system. Subjects arms were placed into the support system and strapped in. Subjects could also position the cell phone so that they could reach the screen comfortably.

4.2.3. DATA ANALYSIS

We performed all statistical analysis using the MATLAB programming software. We used linear regression analysis between each of the somatosensory deficits (proprioception and tactile acuity), and each clinical assessment of hand function (BBT, MAL) and between each somatosensory deficit (tactile acuity vs. proprioceptive error).

4.2.4. RETROSPECTIVE STUDY ANALYSES

For some results presented below, we combined data from two additional studies that measured proprioceptive error using the crisscross method and the FINGER exoskeleton [35], [152]. Tactile acuity data was not available from these studies, but subjects were evaluated for their power grip and MVC and with the BBT and MAL evaluation tools. It should be noted that the two studies were interventional studies, but all data that we used from these two studies were baseline data prior to the use of any intervention.

4.3. RESULTS

4.3.1. FINGER POSITION VERSUS TOUCH SENSING

There was not a significant correlation between the tactile acuity and proprioception error (Fig. 19). Proprioception error neared significance ($p = 0.06$) as a predictor for the BBT score and significantly predicted both subscales of the MAL (AoU: $p = 0.03$; QoM: $p = 0.04$) (Fig. 20 top). Tactile acuity was not correlated with either the BBT or MAL (Fig. 20 bottom).

Figure 19. Proprioception error plotted against the tactile acuity scores. As mentioned previously percent accurate response is the number of times a subject correctly responded to the vibration divided by the total number of times the vibration was presented

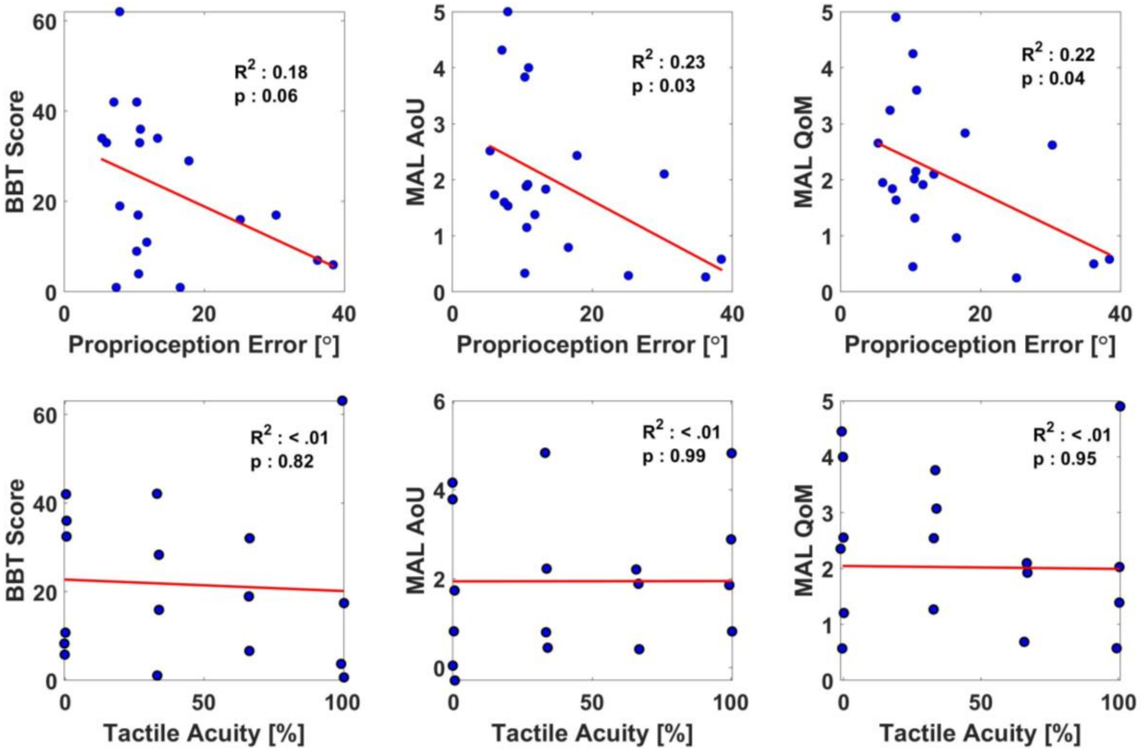

Figure 20. Top) Proprioception error is plotted against BBT scores as well as both subscales of the MAL. **Bottom)** Tactile acuity is plotted against BBT scores as well as both subscales of the MAL. Here we denoted tactile detection deficits as the number of times a subject correctly responded to the vibration divided by the total number of times the vibration was presented

4.3.2. PROPRIOCEPTION, FINGER STRENGTH, AND MOTOR FUNCTION

We had previously acquired finger proprioception and finger strength data with the same methods from an additional 48 subjects. We combined this data along with the current data to more closely examine the relationship of finger proprioceptive deficit to hand function.

First, we evaluated if finger strength was related to proprioception deficit (Fig.10). We found that the two were not correlated.

Next, we tested to what extent finger proprioception predicted hand function, comparing it to the predictive power of finger strength. Finger MVC was a statistically significant predictor for each functional assessment as was finger strength (Fig. 21 Bottom). The amount of variance explained by finger proprioception (0.15 across the three measures) was similar to the amount explained by finger strength (0.19 across the three measures) (Fig. 21).

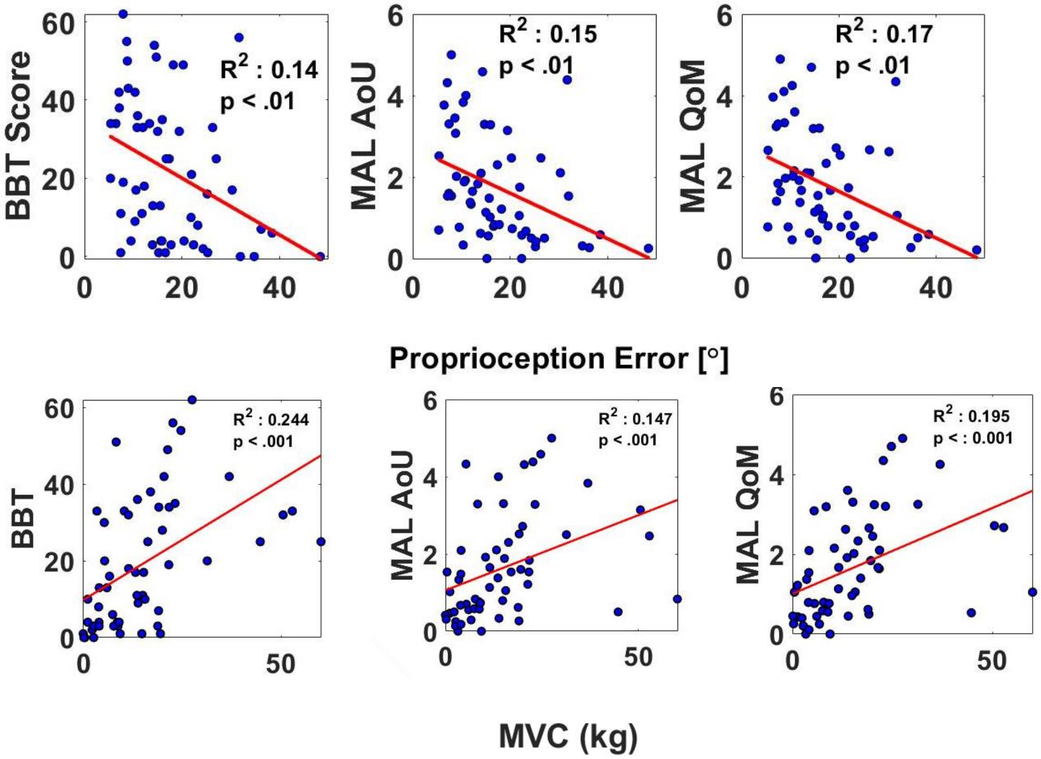

Figure 21. Top) Proprioception is plotted against BBT, and both subscales of the MAL. **Bottom)** MVC is plotted against BBT, both subscales of the MAL, and against proprioception. For both the top and bottom plots linear regression analysis was performed, and the corresponding R^2 values, and p-values are shown.

Finally, we considered what the odds were of achieving a minimum score level on these different clinical assessments when a subject's proprioceptive error falls within a given range. We calculated these odds for a range of scores on the different clinical assessments to explore how these odds change as a function of proprioceptive ability. We found that a power function fit the data well in comparison to other fits that were tested (rational, linear, exponential) (Fig.22). That is, the odds ratio declined nonlinearly. When finger proprioception was normal, stroke survivors had 6 to 1 odds of avoiding the most severe loss of hand function (BBT < 10, MAL < 1), but their odds dropped precipitously to below 2 to 1 as finger proprioception acuity decreased.

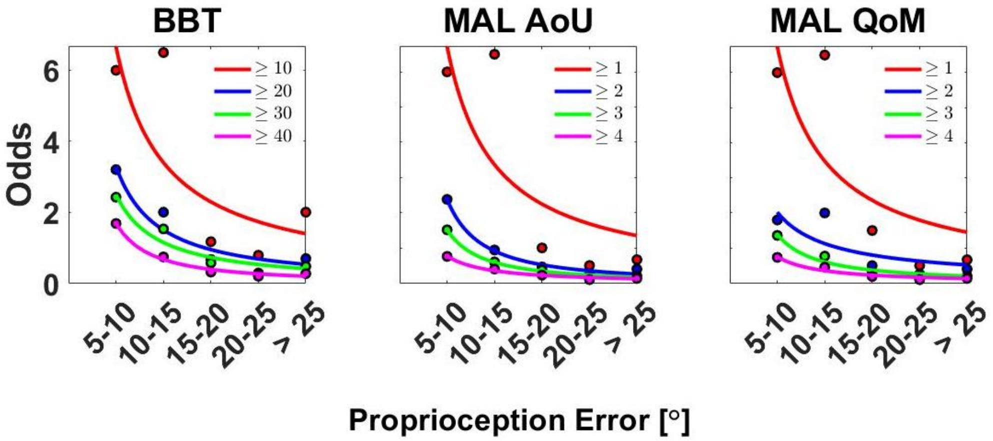

Figure 22. Top) Proprioception error is plotted against BBT scores as well as both subscales of the MAL**. Bottom)** Odds of achieving various scores on the different clinical assessments are plotted against five different bins that represented a range of proprioception error. Additionally, for each of the scores on the different clinical assessment a power function of the form $y = ax^b$ was fit to the data. The data in this plot is a combination of the data from the present study, and archived data from two previous studies. In those two other studies subjects had similar levels of impairment and were also persons with chronic stroke. Here we determined which function fit the data best by comparing the R^2 value as well as comparing the root-mean squared error (RMSE).

4.4. DISCUSSION

4.4.1. PROPRIOCEPTIVE DEFICITS AND THEIR RELATIONSHIP TO MOTOR FUNCTION: IMPLICATIONS FOR NEUROREHABILITATION AND PROPRIOCEPTION TRAINING PARADIGMS

Using the FINGER exoskeleton we identified finger proprioceptive error as a statistically significant predictor of hand function measured via the BBT and MAL. To our knowledge we have only found one other study that has examined the correlation between motor function and a robotic measure of proprioception. Specifically, Cherpin et al. found a correlation between upper limb proprioception measured using a planar robot and Action Research Arm Test in a study with chronic stroke survivors [122]. The results of both studies are consistent with earlier works that measured proprioception using the standard clinical assessment. Given these results this would suggest that proprioception is correlated with motor function in the chronic stroke population, and methods to retrain proprioception should be further explored. This finding also has implications for how we develop rehabilitation therapy programs involving robots. The number of robots developed for rehabilitation after stroke has increased over the years but the results of using these robots in rehabilitation are often variable. For example, in the study conducted with the Inmotion 2 robot, 127 chronic stroke survivors with moderate-to-severe upper extremity impairment were separated into three different groups; intensive robotic-assisted therapy, intensive comparison therapy, and usual standard of care. At 12 weeks the difference between the three different therapies were not statistically significant although Fugl-Meyer scores at 12 weeks were higher for patients in the robot-assisted group [153]. Similar results were also seen in another large study with chronic stroke survivors using the ARMin Hand exoskeleton. 77 chronic stroke survivors with upper extremity impairment were enrolled in the study. Patients were separated into two groups, one receiving robot-assisted therapy and the other receiving conventional therapy with each group receiving at least 45 min therapy sessions three times a week for 8 weeks. At the end of the study subjects in the robot-assisted therapy group reported greater improvements in motor function, however the difference between the absolute effects of robotic and conventional therapy was small, and not statistically significant [154]. But, as was previously mentioned in the introduction, in a previous study we conducted in our lab we saw that those who benefitted most from robotic therapy training had intact proprioception [35]. Thus, a future line of research could assess patient's proprioceptive deficits first using these new more rigorous methods, and then for the subjects who have poor proprioception, work on retraining proprioception, prior to enrolling them in a robotic therapy study. This new step could potentially improve the results of such robotic therapy programs.

Another observation from this study was the nonlinear relationship between the hand function and proprioception error. This suggests that small incremental increases in proprioceptive benefits obtained via training likely will not play a significant role in increasing scores on clinical assessments. To give an example, in the present study we saw that the odds of achieving a score of 20 on the BBT score was < 1 until subjects were in the proprioceptive error range of 5-15°. From our previous study conducted with the FINGER exoskeleton we observed that for adults between the ages of 30-60 they had a proprioceptive error on average of 8° [142]. Thus, to achieve a score of 20 on the BBT, the individual would need to retrain their proprioception until it was comparable to normative function. For some individuals this would mean reducing their error by anywhere between 33-56%.

4.4.2. TACTILE DEFICITS VS. MOTOR FUNCTION AND PROPRIOCEPTION DEFICITS

Tactile acuity was not found to be a statistically significant predictor of motor function. Also, we found that tactile acuity was not a predictor of how subjects performed on the proprioception task. However, although we do not find a relationship between the two, we cannot conclude if there is no relationship between other forms of tactile deficits and proprioception. Further a possible explanation for why we may not have seen a relationship between the two could have been in how the test was administered. Using a cellphone allowed us to reliably deliver vibrations with known frequencies to individuals, and objectively determine if they were able to detect the vibration. However, we only tested three different vibration frequencies, and of those frequencies subjects only felt each vibration three times. Administering the test in that manner lacks sensitivity, while also suffering from floor, and ceiling effects. One other possible explanation for why we did not see a relationship could because we were compared sensory deficits in the finger to that of the thumb. There exists some research that suggests that the thumb, and the finger can be affected differently after stroke. For example, Kamper et. al identified that there is a lack of hypertonia in the thumb as compared to the fingers [107]. Thus, the comparison of finger proprioception to thumb tactile ability may make interpretation of the results of the regression model between the two difficult. To gain better insight into the relationship between the two, future work could examine finger proprioception versus finger tactile discrimination and thumb proprioception versus tactile discrimination as this may be a better comparison.

4.4.3. MVC AND ITS RELATIONSHIP TO MOTOR FUNCTION, AND PROPRIOCEPTION

In the literature it has be observed that grip strength is a predictor of motor function. Our results in the present study are consistent with this notion as well. We also found that proprioception is a predictor of motor function as well. But some studies argue that proprioception is not an independent predictor of motor function. This notion is based on evidence from studies that showed when multiple linear regression analysis is performed, and strength or motor performance are included in the model proprioception is no longer a significant predictor [155]–[157]. This would suggest the relationship between proprioception and motor function exists only because there is a correlation between strength, and proprioceptive deficits. However, linear regression analysis showed that there was not a significant relationship between proprioceptive deficits and strength. This would indicate that both strength and proprioception are independent predictors of motor function.

4.5. CONCLUSION

The results of this study showed that proprioception specifically finger position sensing measured using a tabletop hand exoskeleton is related to motor function in chronic stroke survivors. We also showed that finger position sensing was not correlated to grip strength, although grip strength was also related to motor function. This suggests that both finger position sensing and grip strength are independent predictors of motor function. Tactile acuity was not related to motor function, nor was it found to be related to finger position sensing. However, future studies should examine how this relationship changes when tactile and finger position sensing are compared between the same digits of the hand. Additionally, a different approach to assess tactile acuity should be used in future studies as the current approach suffered from floor, and ceiling effects. Finally, we found that the odds of achieving various scores on clinical assessments of hand function decayed nonlinearly as a function of proprioception error suggesting that substantial improvements in proprioceptive ability may be necessary in order to significantly improve scores on clinical assessments.

CHAPTER 5. DESIGN AND CONTROL OF A NOVEL GRIP AMPLIFIER TO SUPPORT PINCH GRIP WITH A MINIMAL SOFT HAND EXOSKELETON

5.1. BACKGROUND

Many hand exoskeletons have been developed to assist hand function [38] however, few have undergone testing with their target population [37]. The lack of testing can be attributed to a number of factors such as cost, complexity, or bulkiness with only a few hand exoskeletons being available commercially. Examples of commercially available devices are: the SEM Glove – a glove that senses force applied to an object then uses this force to amplify finger flexion forces via tendons running through the glove [159]; the Daiya glove – 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; and the SaeboFlex – a rigid orthosis that relies on springs to assist with extension of the fingers and thumb. Such devices although promising still to have several limitations. As mentioned, most of these devices are bulky. Many devices also cover the finger pads limiting haptic input to the user; the SEM glove is an exception as it leaves the index and little finger uncovered. Perhaps most importantly, many devices lack intuitive control, often relying on switch-based control, meaning that the user must use another movement or action to initiate hand assistance. In large part, it is still unclear how a person with a stroke can best achieve intuitive control of a hand exoskeleton.

In chapter 3 we showed that stroke survivors possess the ability to precisely control isometric grip force. We now discuss additional observations that in combination with the results from chapter 3 provide a rationale for a control strategy suitable for a minimalistic hand exoskeleton. By “minimalistic” we mean a device that only partially covers the hand. We first present four key observations that arose from experiments conducted in our laboratory, which provide evidence for the potential of a “residual force control” (RFC) strategy. We then describe a preliminary experiment in which we tested the RFC strategy with a high-fidelity tabletop exoskeleton with unimpaired people. Finally, we present progress on actuator development for a soft exoskeleton for implementing the RFC strategy.

5.1.1. RATIONALE FOR A RESIDUAL FORCE CONTROL STRATEGY

5.1.1.1. PINCH GRIP ALONE IS SUFFICIENT TO SCORE WELL ON CLINICAL SCALES OF HAND FUNCTION

In a pilot study, we asked 11 unimpaired participants to perform two clinical tests of hand function; the Box and Blocks Test (BBT), and the Jebsen-Taylor Hand Function Test (JHFT). The BBT is a widely used clinical assessment of hand function in stroke rehabilitation that measures the number of small blocks a person can lift and move over a divider in one minute [149]. The JHFT is a more comprehensive test, which measures the time required to complete seven different tasks that simulate activities of daily living. Participants performed both tests using their whole hand (WH), thumb-index pinch grip (TIPG), and lateral key pinch grip (LPG), enforced with splints [160]. During the BBT we measured the percentage decrement in number of blocks moved with each grip type as compared to the whole hand. Participants achieved on average 80 ± 6 % and 60 ± 6 % of their whole hand score on the BBT with the thumb-index grip and lateral pinch grip respectively (Fig. 23A). For the JHFT, there was a 15 ± 10 % increase in task completion time using the thumb-index pinch grip, and 46 ± 19 % when using the lateral key pinch grip (Fig. 23B). At face value it would be easy to say that one should put forth the effort in developing a hand exoskeleton that focused on assisting all five fingers as you can achieve the most functionality with the whole hand. But assisting the movement of all five fingers requires a bulky and obstructive device that would likely cover the hand. Moreover, it is likely that this enhanced bulk would lead to only marginal improvements in functionality, as it is well documented that only a small subset of grip types are necessary to perform most activities of daily living [41]. Thus, assisting a single grip, the thumb-index pinch grip, might provide enough hand function for many daily activities. This finding is also consistent with what is seen with upper extremity prosthetics. 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” [161].

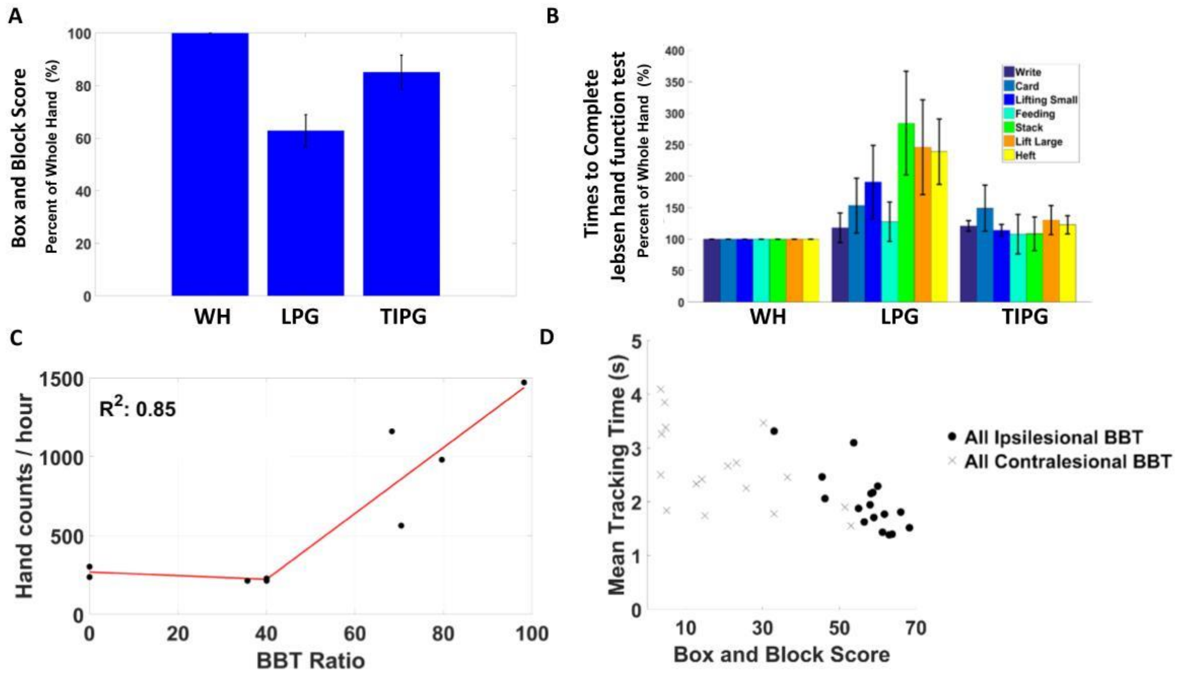

Figure 23. A) Box and Block Test scores when unimpaired participants perform the test using their whole hand (WH), thumb-index pinch grip (TIPG), and lateral key pinch grip (LPG), plotted as a percentage of WH score. **B)** Jebsen-Taylor Hand Function Test scores (task completion time) for the three different grip types, plotted as a percentage of WH hand score **C)** Amount of hand movement measured with a wearable sensor (the Manumeter), measured as hand counts per hour) plotted a function of their Box and Blocks Test (BBT). Data measured from nine individuals with chronic stroke who wore the Manumeter for 12 hours at home. BBT is plotted as the ratio of the score of the impaired hand to the score of the unimpaired hand. Below a ratio of about 0.5, the participants rarely used their hand (200 counts are about noise level for an inactive hand). **D)** Relationship between Box and Blocks score, and time required to acquire a grip force window displayed on a computer screen. Data is from 17 individuals who used power grip to squeeze a force transducer. Target force levels ranged from 3-30%, and window widths 1.5% to 3% of Maximum Voluntary Contraction (MVC).

5.1.1.2. THERE IS A THRESHOLD LEVEL OF HAND FUNCTION NEEDED TO INCORPORATE THE HAND INTO DAILY ACTIVITIES

Although it appears that assisting TIPG has the potential to allow people to achieve substantial hand function, the question remains whether this amount of hand function would be sufficient to drive daily use of the hand. We recently gained insight into this question with the Manumeter, a non-obtrusive wearable sensor consisting of a wrist unit, shaped like a wristwatch, and a magnetic ring. The Manumeter is capable of detecting finger flexion/extension, wrist radial/ulnar deviation, and wrist flexion/extension [162].

Nine participants with a chronic stroke wore the Manumeter on the wrist of the paretic arm for 7.7 ± 0.9 hours at home and in the community. We quantified the number of times they moved their hand beyond a small threshold amount of movement each hour. We found a non-linear relationship between the amount participants used their hand and their hand function measured with the BBT (Fig. 23C). Below a threshold of about half normal score on the BBT, people rarely used their hand. Above this threshold, we observed linearly increasing hand use as a function of BBT score. This suggests that for people to use the impaired hand in their daily life, they need the impaired hand to be at least half as functional as their unimpaired hand, measured in terms of the BBT. This is a potential target for a minimalistic exoskeleton that appears achievable using TIPG (Fig. 23 A, B).

5.1.1.3. PEOPLE WITH SEVERE HAND IMPAIRMENT AFTER STROKE HAVE A SURPRISINGLY WELL-PRESERVED ABILITY TO CONTROL ISOMETRIC FINGER FLEXION FORCE

Our lab and others have shown that people with stroke can accurately modulate flexion forces with their fingers, as long as the fingers remain isometric [104]–[106]. In a recently published study previously conducted in our lab we asked 17 people with 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 height set to 3 – 30 % of MVC , and target width set to 1.5 – 3.0 % of MVC [105]. We measured the average time it took participants to reach the various target levels, and we observed that even participants with BBT scores as low as 3 could regularly acquire the target (Fig. 23D). In addition, other research shows that, as soon as finger movement is allowed, force production drops dramatically, particularly during finger extension [163]. Thus, isometric flexion force is potentially a source of high-fidelity force control signaling still available after stroke, but it must be translated into finger movement (and especially finger extension) to facilitate hand use.

5.1.1.4. FORCE GENERATION IS HIGHLY CORRELATED BETWEEN FINGERS WITH IMPAIRMENT AFTER A STROKE.

Using the FINGER exoskeleton [164], we recently showed that the index and middle finger generate highly correlated forces (Fig. 24), when participants with a severe stroke were asked to generate forces with the fingers independently [120], consistent with the concept of abnormal synergy. This suggests 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.

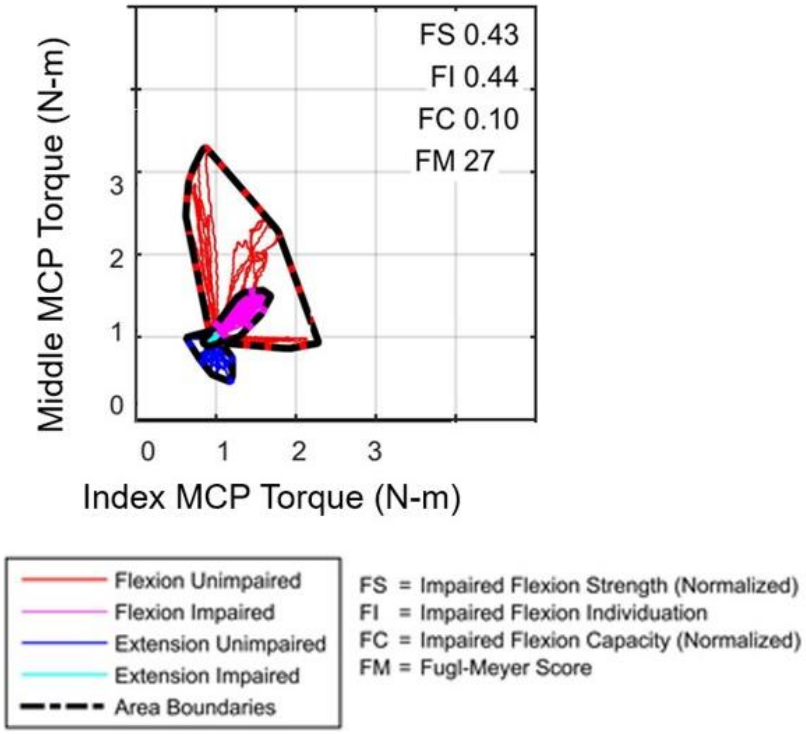

Figure 24. Finger flexion torques are correlated for people with severe hand impairment after stroke. This plot shows a representative example of metacarpal-phalangeal joint torque during a maximum voluntary contraction of the index finger alone, the middle finger alone, and both fingers together, in both flexion and extension (reproduced from). Shown are data from a single subject with an upper extremity Fugl-Meyer score of 27 out of 66, for their unimpaired hand (flexion in red and extension in blue) and their impaired hand (flexion in magenta and extension in cyan). Note the difficulty generating extension torques. However, the subject could generate substantial flexion torques with the impaired fingers. For all three movement conditions (index finger alone, middle finger alone, both fingers together) the index and middle finger generate torques that were highly correlated with each other for the impaired hand. This suggesting it might be intuitive to use the torque generated by one finger to amplify the torque generated by the other finger for people with severe hand impairment after stroke.

5.2. PILOT TEST OF RESIDUAL FORCE CONTROL STRATEGY WITH UNIMPAIRED SUBJECTS

Based on the observations presented in the previous section, we propose an RFC strategy to support pinch grip with a minimalistic exoskeleton. Specifically, we propose measuring the isometric flexion force produced by digits 3-5 (middle-little finger) against the palm of the hand to control an exoskeleton assisting in pinch grip. Using a fixed-base exoskeleton, FINGER, we pilot tested this RFC strategy. We tested if unimpaired subjects could intuitively use the RFC strategy, whether they could improve their performance with feedback, and whether use of RFC altered the normal grip force modulation strategy used during object manipulation.

5.2.1.*METHODS*

5.2.1.1. EXPERIMENTAL SET UP

We tested the RFC strategy using the FINGER exoskeleton and a custom-made pneumatic pressure sensor [165] with five unimpaired, right-handed participants. The FINGER exoskeleton is large and bulky, but it 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 participants to flex and extend the elbow to lift an object instrumented with a 3-axis accelerometer and single-axis force transducer (Fig. 25, Left). Additionally, a thumb splint was worn by participants which held the thumb in opposition (Fig.25).

5.2.1.2. CONTROL ARCHITECTURE

The controller used in this study is implemented in MATLAB xPC Target, with a sampling frequency of 1 KHz. A National Instruments 6221 DAQ card (16-Bits, 250kS/s) was used to acquire voltage signals from the accelerometers, loadcell, 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. 25, Right).

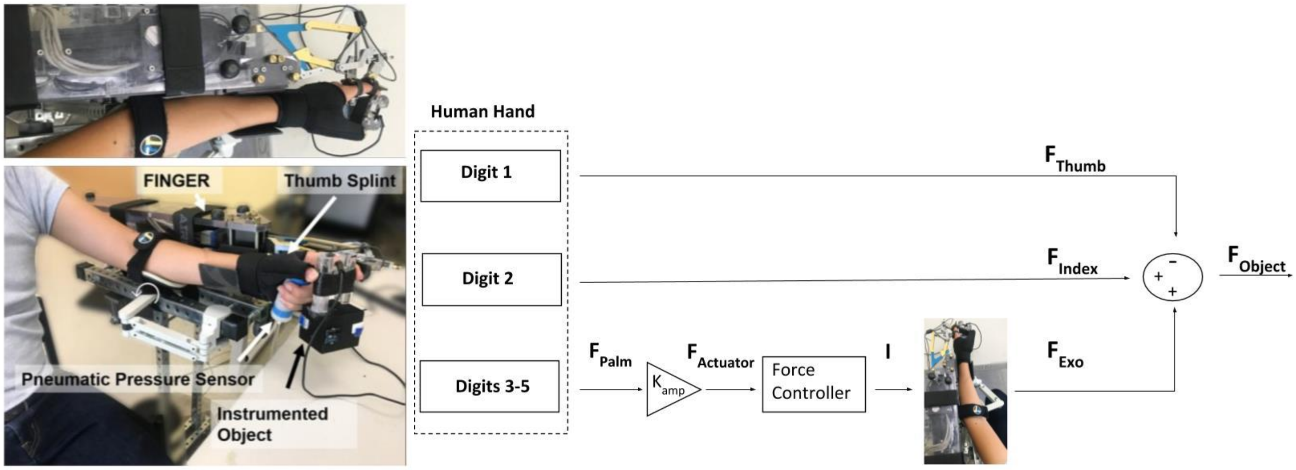

Figure 25. Left) Experimental setup. The FINGER exoskeleton was mounted on the custom-built arm support which enabled flexion and extension of the elbow, allowing subjects to lift instrumented object in a vertical plane off the table. A pneumatic pressure sensor is used to measure $F_{palm.}$ **Right).** Control diagram of the RFC strategy. When digits 3-5 are pressed against the pneumatic pressure sensor the signal F_{palm} is created. This signal is amplified by a gain Kamp and fed into a force controller. This force controller sends out an actuator force ($F_{actuator}$) to the linear actuator which moves the 8-bar mechanism. The combination F_{Exo} and F_{index} is measured with the load cell in the instrumented object.

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 gain was selected such that $F_{Exo} = 2F_{palm}$. Note that F_{Exo} differed from $F_{actuator}$ because of static friction in the exoskeleton. Additionally, the force applied to the object (F_{object}) could be diminished compared to F_{Exo} if the angle the finger made with the force transducer varied from being perpendicular. Assuming the finger was orthogonal to the object, the total force applied to the object was:

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

where F_{index} was the force produced by the index finger and is inferred with (2), F_{thumb} is the force produced by the thumb which counteracted the force produced by F_{index}, and the total grip force (i.e. F_{object}) is measured using the instrumented object.

5.2.1.3. EXPERIMENTAL PROTOCOL

During the experiment subjects were fastened into the FINGER robot. Note that the FINGER exoskeleton left the glabrous surface of the index finger free, so participants could sense tactile interactions with the object. Participants then performed 5 sets of 5 lifts for 10 seconds each, first with no exoskeleton (*"hands only"* condition), and then with the RFC (*"Exo" condition)*. When the exoskeleton was on and participants were using the RFC strategy, participants were asked to perform the lifting task with the goal of minimizing F_{index} and maximizing F_{Exo}, Afterwards, 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. We provided this feedback to determine if they could improve their ability to make use of the exoskeleton over time to amplify their grip force.

5.2.2. *RESULTS*

Participants were able to intuitively use the RFC strategy to pick up the object from the first lift of the first set, and never dropped the object. Across sets, they gradually learned to control the exoskeleton, so it did more of the squeezing, up until the exoskeleton was applying about 90% of the object force (Fig. 26, Left, Repeated Measures ANOVA, $p < 0.004$). However, the grip force pattern with the RFC was significantly greater than when the participants lifted the device without the exoskeleton (Repeated Measures ANOVA, p

< 0.001, Fig. 26, right). Additionally, the grip force during each lift decayed less slowly during RFC (Fig.26, Right) and the peak grip force increased across sets.

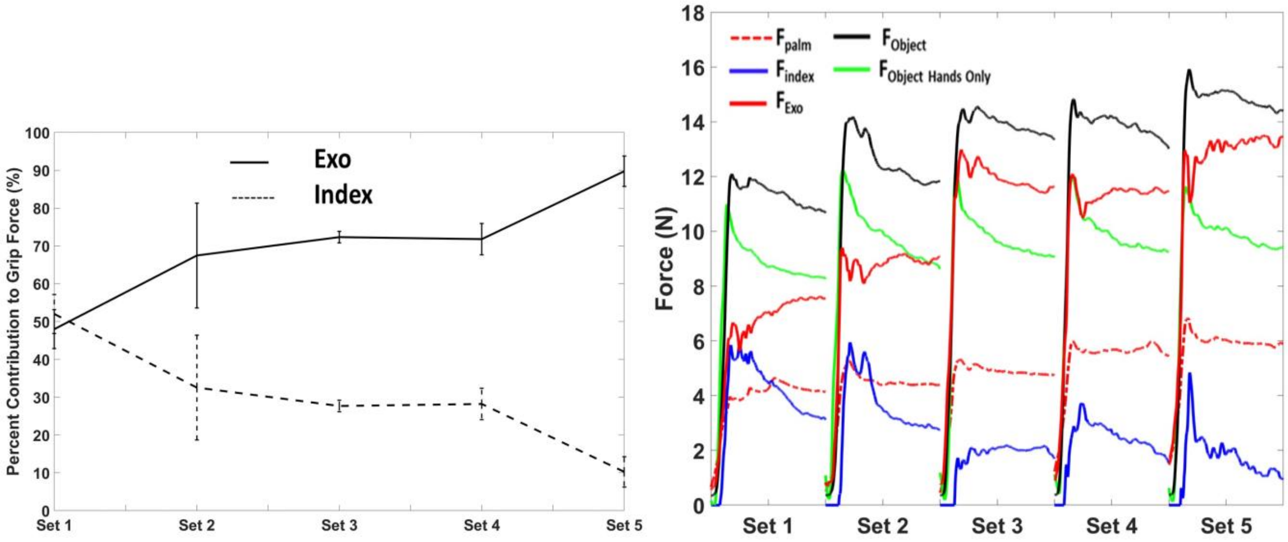

Figure 26. Left) Percent contribution to grip force versus set number. **Right)** Various forces measured during the experiment versus time, where each force trajectory is the time-averaged force across the five, 10-second-long lifts performed in each set. F_{Object} hands only is the object force when the subjects lifted the object without using the exoskeleton.

5.3. ACTUATOR DEVELOPMENT FOR A MINIMAL SOFT FINGER EXOSKELETON

5.3.1. BACKGROUND

In parallel to verifying the feasibility of the RFC strategy, we began to prototype a soft exoskeleton for assisting in pinch grip focusing first on the development of the actuation mechanism. We determined that the first step in designing the soft actuator would be to determine the amount of force necessary for the actuator to produce. A study from Matheus et al. benchmarked grasping and manipulating forces with 64 different objects that people interact with in daily living [109]. Of those objects, 54 of them were less than 500g with the average weight being 275 ± 302.9 g and the maximum weight being no more than 1.5 kg. Taking 500 g as the desired maximum weight of the object to be lifted by the soft exoskeleton, our previous experiment described in Section 5.3 suggests the actuator used in the design needs to produce a grip force of about 12 N.

5.3.2. ACTUATOR DESIGN AND TESTING

In this initial design we explored the use of a fiber reinforced (FR), soft, bending actuator [166] due to its compliance, comfort, and wearability. We fabricated two versions of the actuator. The first version was designed to assist in index finger flexion (Fig. 27A). It used a semi-circular cross section, replicating the design that was initially proposed by et. Al Galloway [166]–[169]. The second version of the soft actuator was designed to assist both index and middle finger flexion, allowing a larger cross-sectional area for the actuator, as well as greater surface area for grasping. The cross-sectional area of the original and modified actuators was 66.6 and 90.6 mm^2, respectively (Fig. 27B). We utilized a high durometer silicone layer for the core rubber layer of the actuator (Dragon Skin 30, Smooth-On Inc., USA), then encapsulated it in a low durometer silicone layer (Eco-flex 00-30 Smooth-On Inc., USA). The outer core of the soft actuator is then wrapped with inextensible fibers. To evaluate the tip force of the actuator we taped the actuators to the back of the index finger (original actuator) or the index and middle fingers (modified actuator). We held the forearm and hand in a splint and placed a load cell (Interface, SMA-200) between the fingers and the splint to measure the force produced by the actuators (Fig. 27D).

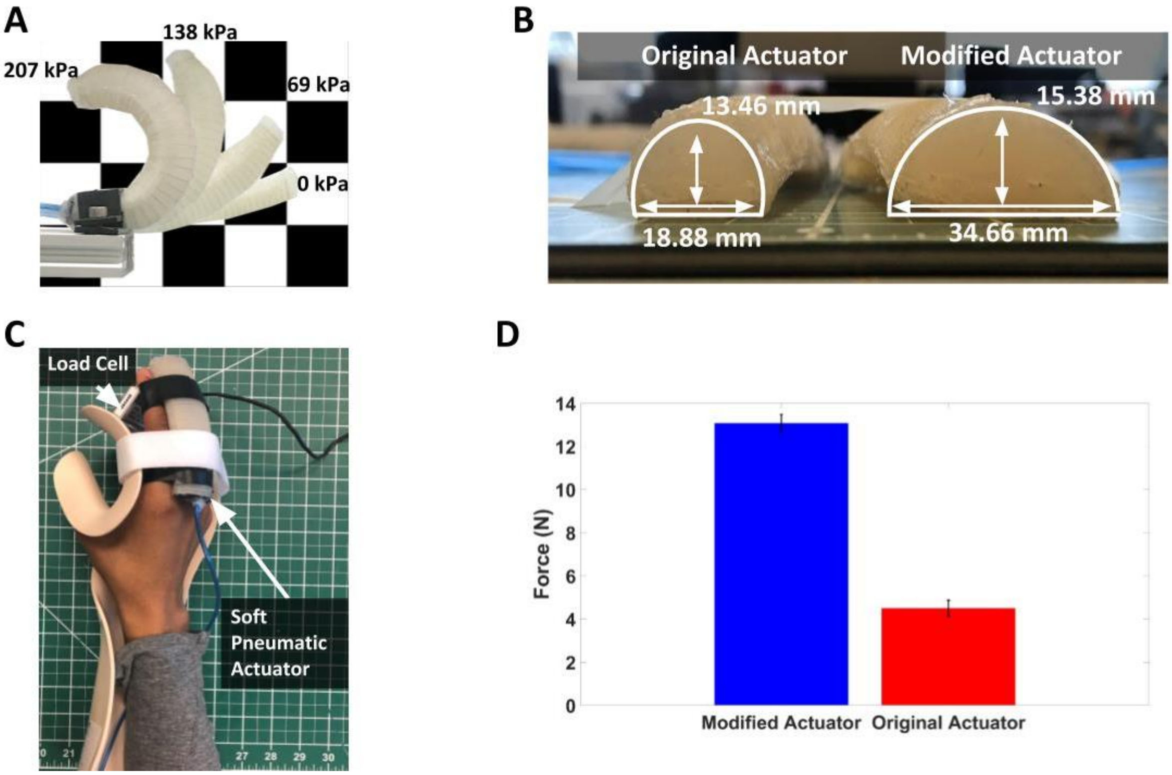

Figure 27. **(A)** trajectory of pneumatic actuator when pressurized at different pressures **(B)** Dimensions of the previous actuator developed by (left), and a modified actuator (right). **(C)** Peak force produced by the original and modified actuator at 207 kPa. **(D)** Picture displaying the experimental setup used to measure actuator force development. The modified (i.e. two-finger) soft pneumatic actuator is shown.

5.3.3. RESULTS

We limited the maximum pressure to 207 kPa (30 psi), as the actuators bubbled and broke at around a pressure of 276 kPa (40 psi). The original FR actuator produced a peak force of 4.49 ± 0.32 N. The modified version of the FR actuator produced 13.06 ± 0.33 N (Fig. 27C). Thus, the modified version was sufficient to meet our goal of achieving the ~12 N grasp force needed to lift a 500 g object. Bending trajectories for the actuator are shown (Fig. 27A).

5.4. DISCUSSION

5.4.1. RATIONALE FOR A MINIMALISTIC EXO AND RFC

We first presented several observations that suggest a possible paradigm shift in the way that hand exoskeletons for people post-stroke are designed and controlled. By assisting a simpler grip, one can potentially achieve a substantial amount of hand function while reducing bulk and complexity and improving appearance of the exoskeleton. Using an RFC strategy also looks promising because it takes advantage of the post-stroke hand’s residual function. We presented evidence that even people with BBT scores as low as three were able to accurately control their isometric finger flexion force. Using this isometric flexion forces as a control source for an exoskeleton may lead to more intuitive control than switch-based control schemes. And it may be intuitive even for people with severe hand impairment, since the force they generate with one finger is already correlated with the force generated by other fingers. This approach differs from the SEM Glove described in section 5.2, which requires users to have enough hand function to shape the hand around an object, or the SaeboFlex, which requires users to have enough finger flexor function to overcome the stiffness of the spring to use the device. Finally, RFC is also attractive because it may be therapeutic – i.e. repeated attempts to control the fingers may improve the ability to control the fingers.

5.4.2. FEASIBILITY OF THE RESIDUAL FORCE CONTROL STRATEGY

Using a high-fidelity tabletop exoskeleton, unimpaired participants were immediately able to use the RFC 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. This result suggests moving on to testing with people with a stroke, which we are currently undertaking. Ideally, any control strategy for a hand exoskeleton would allow users to preserve their normal pattern of grip force when lifting an object. Typically, during object manipulation, the grip force rises until it reaches peak force coincident with the maximum upward acceleration, before falling exponentially until slip is detected. However, in this study subjects altered their grip force trajectory when using the RFC strategy in a manner consistent with becoming more conservative against the object slipping (i.e. by applying a slightly larger, less dynamic force) [97]. Subjects also may have increased F_{object} across practice sets because doing so decreases the ratio F_{index} / F_{object}, which they were shown using visual feedback and asked to minimize.

5.4.3. TOWARD SOFT ACTUATION FOR A MINIMALISTIC HAND EXO

Modeling analysis predicts the force produced by the FR actuator increases with the cube of cross-sectional area [167]. We found slightly better results: the cross-sectional area of the modified actuator was 1.36 times greater than the semicircle actuator, predicting a force increase factor of 2.51, less than the 2.87 observed. This may be because we changed the shape of the actuator as well as its area: the modeling analysis notes that a FR actuator with a rectangular cross-section can be narrower and shorter and produce similar torque to the semi-circular design. In any case, if we are to use a FR actuator at 30 PSI, and desire 12 N of grasp force, a viable route is the minor segment shape assisting yoked index/middle finger flexion. Moving forward, we plan to use compliant-as-possible springs to assist in hand opening. Hand closing will be triggered by measuring force from digits 4-5 force, increasing pressure in the FR actuator mounted over digits 2-3. Working out a portable and wearable air supply is another important direction.

CHAPTER 6. IGRIP: A MINIMALISTIC HAND EXOSKELETON CONTROLLED USING RESIDUAL ISOMETRIC FORCE CONTROL STRATEGY

6.1. INTRODUCTION

There have been several attempts to provide intuitive and roboust control to hand exoskeletons. In a recent review published in 2016 by Bos more than 165 hand exoskeletons were identified [38]. Of the hand exoskeletons identified surface electromyography (sEMG) and switch-based control dominated the realm of control strategies used in hand exoskeletons. The use of surface EMG has yielded some success, and the few hand exoskeletons that are available commercially such as the Myo pro hand orthosis rely on sEMG. However, sEMG does have its limitations. For example, classification of the signals can be difficult and often requires advanced machine learning algorithms which can be computationally expensive. sEMG also requires careful placement of the electrodes as signals can be affected by artifacts such as sweat or the hair that is present on the skin. Also using sEMG also tends to require training time for the user to learn how to appropriately use the device which can be time consuming. Switch based control is very simple and easy to implement in a hand exoskeleton. However, switch-based control requires the user to use the other hand to initiate movement of the impaired hand which can become tedious and is not very intuitive. Thus, it remains unclear how best to go about delivering robust and intuitive control to a hand exoskeleton. Recently, our lab has developed a novel control strategy: residual force control, which relies on using the intact isometric grip force control ability in the impaired hand. We recently showed with a traditional rigid exoskeleton that unimpaired individuals are able to take advantage of the force controls and use it to improve performance on a given task.

However, another issue that can arise outside of the selection of a control strategy is also the mechanical design of the exoskeleton. Today most exoskeletons by in large remain bulky and obtrusive. One reason for this could be in the type of grip chosen to facilitate. Many exoskeletons try to facilitate a power grasp requiring actuation of all five fingers. Although this maybe more natural to the human hand, there are other grasp types that have fewer degrees-of-freedom, and still afford a high degree of functionality. For example, in a study conducted by Dollar et. al it was shown that throughout the course of a day there exist a small subset of grasps that a machinist and nanny used to complete a wide variety of tasks [39], [40], [174]. Further there have been other labs that have shown that grasps such as a pinch grip or a lateral pinch grip which only require actuation of two digits have been able to give the user a decent amount of functionality [175]. This is analogous to what we see in prosthetics. For example, in the latest cybathalon competition, an international competition in which people with physical disabilities compete against each other to complete everyday tasks it was not the high DOF myoelectric prostheses that won the competition. But the terminal body powered hook. Two things that stand out about the hook are its simplicity in both design and control. We decided to explore that concept further by developing a hand exoskeleton called the IGrip which relies on a simple body powered control strategy and actuates just a pinch grip. Here we discuss the control strategy, the design of the exoskeleton, preliminary tests with the exoskeleton as well as future directions.

6.2. OVERVIEW OF HAND EXOSKELETON

The hand exoskeleton is composed of a soft actuator connected to a linear actuator (PQ12-R, Actuonix). The exoskeleton has one actuator that is placed on the lateral side of the index finger and is used to facilitate a pinch grasp. The thumb is held in opposition using a ball and socket joint that is attached to the side of the exoskeleton. Users can rotate their thumb to the desired position and then lock it in place once they are in a comfortable position. A thumb splint is also connected to the ball and socket joint. This splint helps to prevent the thumb from stiffening or “trigger thumb” during the grasping task (Fig. 28). The exoskeleton is controlled using the residual force control strategy (RFC) was previously mentioned chapter 5 of the dissertation.

A custom built printed circuit board (PCB) houses the microcontroller (Teensy 3.2) which is used to implement the control strategy and acquire data from the force sensor. Additionally, the PCB has a loadcell amplifier (INA 125P) , and two boost voltage regulators. The entire system is powered using a 3.7V Lithium-ion polymer battery.

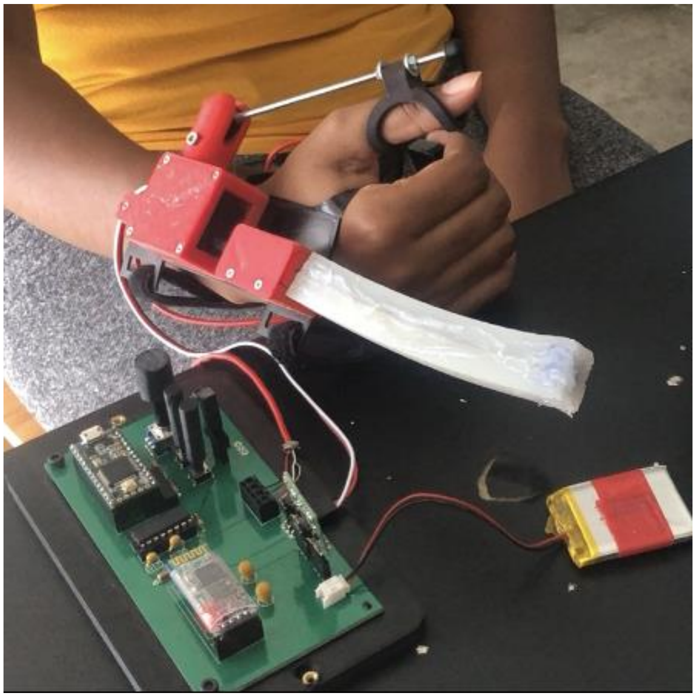

Figure 28. The IGRIP hand exoskeleton. The IGRIP hand exoskeleton is comprised of a novel soft actuator, and a force sensor along with the body of the exoskeleton. The exoskeleton itself is controlled using a residual force control strategy which requires the user to squeeze on the force transduce in order to control movement of the soft actuator.

6.3. SOFT ACTUATOR

6.3.1. MECHANISM STRUCTURE AND FABRICATION

There are several different actuation strategies that have been explored in the design and development of hand exoskeletons. Common actuation strategies include: soft fluidic actuators using either water or air as the fluid, electromagnetic actuators such as rotary or linear actuators, electroactive polymer actuators, twisted and coiled polymer actuators, shape-memory alloy actuators, shape-memory polymer actuators, and piezoelectric actuators. However, at present exoskeleton designs have been dominated by the use of either electromagnetic actuators or soft fluidic actuators. Soft fluidic actuators using either water or air have excellent power to weight ratios. The inherent compliance of soft fluidic actuators is also an attractive attribute but, fluidic actuators applications require the use of bulky auxiliary systems such as pumps and regulators which have limited their use to tethered applications. Electromagnetic actuators such as linear or rotary actuators are a reliable, but require a transmission mechanism such as tendons or linkages. Rigid linkages offer a robust way to transmit forces, but are inherently bulky. The use of tendons as a transmission mechanism is attractive due to its form factor. But, tendon mechanisms typically can only transmit forces uni-manually thus increasing the complexity of the design if forces are to be transmitted bi-manually. Recent work conducted by Arata [176], suggests that compliant mechanism may be another alternative transmission mechanism for electromagnetic actuators. Compliant mechanisms are flexible mechanisms that can achieve force and motion transmission through elastic body deformation. Complaint mechanisms also can be designed as compact monolithic structures allowing them to be lightweight, require no lubrication, and do not have backlash. For these reasons we chose to explore the use of a compliant mechanism connected to a linear actuator in the design of our hand exoskeleton. For the remainder of the chapter soft actuator will refer to the combination of the compliant mechanism and the linear actuator.

The mechanism we developed is composed of three different layers. The bottom layer is composed of a low durometer silicone rubber (Eco-flex 00-30, Smooth-On Inc., USA). The top layer is composed of a higher durometer silicone rubber (Dragonskin 30, Smooth-On Inc., USA).In between the two layers there is a channel that allows for the sliding of a piece of spring steel (Fig.29). In order to fabricate the structure, we first had to make the silicone rubber body of the actuator. We created the silicone mixture for the Eco-Flex 00-30 first as this forms the bottom layer of the actuator. Prior to pouring the silicone mixture we created the channel for the spring steel. To do this we wrapped the spring steel in tape and coated it with Vaseline. This was then inserted a slot on the mold. After the spring steel was placed in position, the silicone mixture was poured into the bottom of the 3D printed mold, sealed, and then allowed to sit for approximately 45 min. During that time, we created the mixture for the top silicone layer composed of Dragon skin 30. Once the Eco-Flex 00-30 layer reached gel time (the initial semisolid phase that develops during the formation of a resin from a liquid) we removed the top of the 3d printed mold and poured in the Dragon skin 30 silicone mixture on top of the Eco-Flex 00-30 mixture. The top of the 3d printed mold was then placed back on to the 3D printed mold, and the complete silicone mixture was given time to cure. In total this process took approximately 14 hrs. Once the curing process finished the structure was removed from the mold. The spring steel was then removed from the silicone so that the tape that was placed around the silicone could be removed. After removal of the tape from the steel, the piece of spring steel was then slid through the channel until it passed completely through the entire silicone structure. A 3D printed rectangular disc is then attached to one end of the spring steel. One the other end of the steel another 3D printed plate is attached in addition to a 3D printed clevis. This clevis attachment is then attached to the linear actuator (Fig. 30)

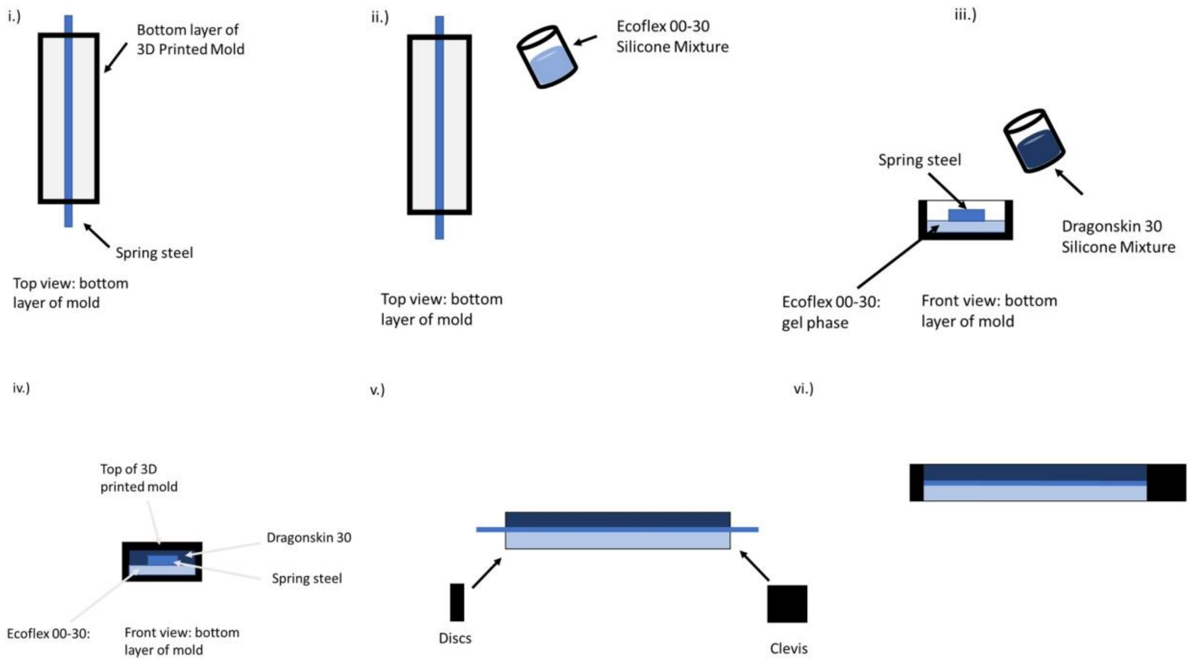

Figure 30. Fabrication process for compliant mechanism. The process can be summarized in 6 steps. **i.)** The 3d printed model has an inlet that allows the spring steel to slide completely through it. The spring steel is placed in this inlet prior fabricating the soft silicone body **ii.)** The silicone mixture for the Ecoflex 00-30 was formed. This forms the bottom layer of the mechanism and is poured into the mold. This layer of silicone is allowed to cure until it reaches gel phase which occurs at approximately 45 minutes. **iii.)** After the silicone is allowed to reach gel time the mixture for the Dragonskin 30 is created. This silicone mixture is then poured on top of the Ecoflex 00-30. **iv.)** Pouring the liquid Dragonskin 30 on the Ecoflex 00-30 mixture before it has fully cured will cause the two mixtures to bond together. The top of the 3d printed mold is then placed onto the bottom of the 3d printed mold to fully encapsulate the combined silicone mixture. This mixture is then given 14 hrs. to fully cure. **v.)** After the mixture has fully cured it is removed from the 3d printed mold. A 3d printed rectangular disc is attached to one end of the spring steel while a 3d printed regular plate is attached to silicone body at the opposing end . There is also a channel in this rectangular plat that allows the steel to slide through the plate **vi.)** Completed compliant mechanism.

6.3.2. WORKING PRINCIPLE

From beam theory, when an axial load is applied to a beam if the load is sufficiently large it will cause the beam to buckle and bow in the center. When you implement an axial load to a cantilever beam it will cause the beam to buckle in one of two directions. However, buckling typically favors the direction that has the smaller stiffness. In this structure we have a cantilever beam that has three different stiffnesses, one from the first layer of silicone, the second coming from the second layer of silicone, and the last stiffness coming from the spring steel. When you compress the beam, the spring steel buckles, but it buckles towards the area that is less stiff which in this case is the bottom layer of the actuator or the softer silicone layer. This causes the actuator to bend in a fashion similar to the human finger (Fig.31).

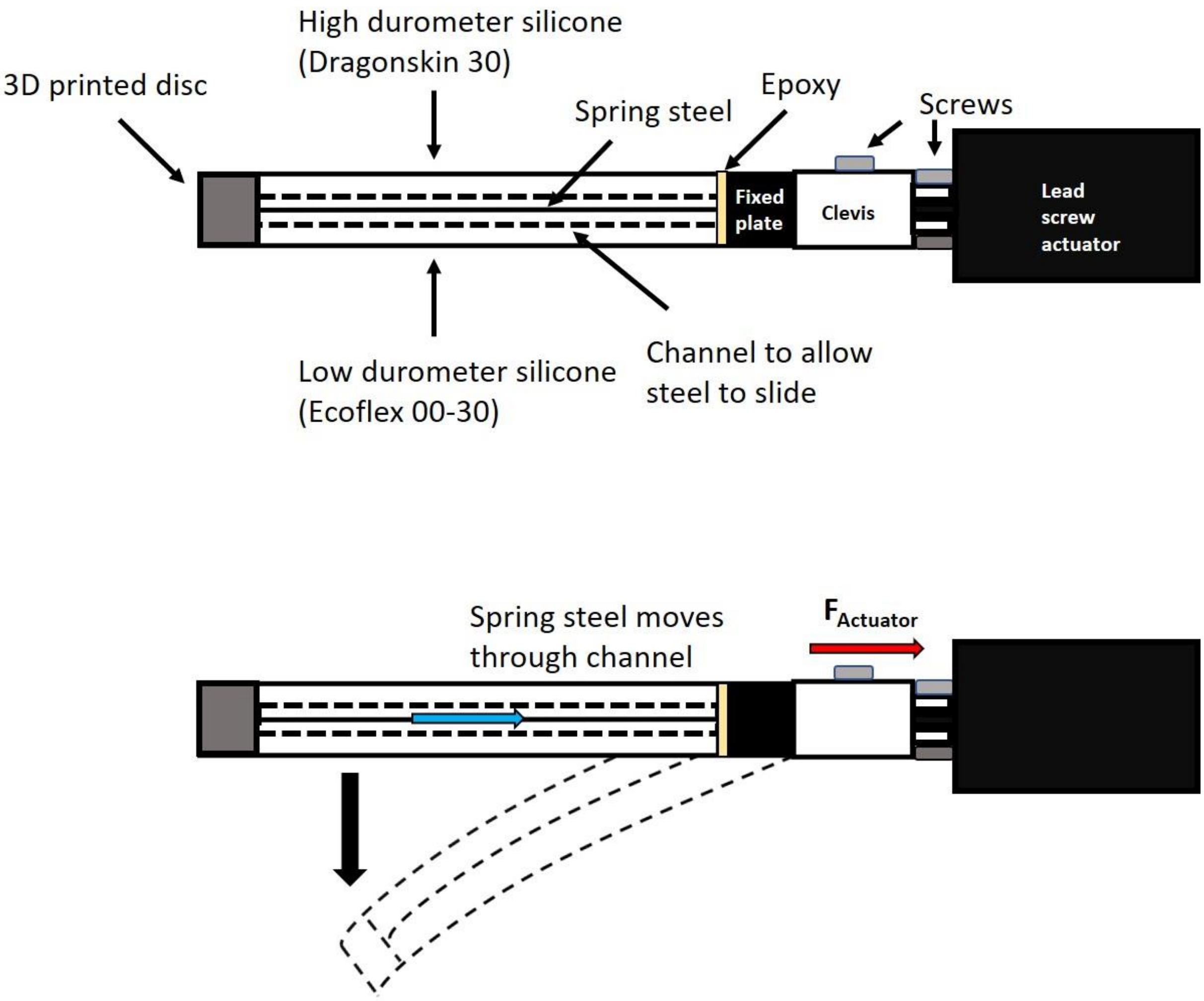

Figure 31. Working principle for compliant mechanism. When the linear actuator applies a force this pulls on the spring steel. This in turn causes the 3d printed discs that are mounted at the end of the spring steel to push the top and bottom silicone layer into the 3d printed plate which is fixed. When the silicone body

6.4. CONTROL STRATEGY

Research in our lab and others has shown that people possess precise control of isometric grip force in the ipsilesional hand when their maximum voluntary contraction is between 10-30% [103], [105], [106]. In a previous experiment conducted in our lab we used this observation do design a control strategy based on the residual isometric force intact in the hand after stroke [175]. The control strategy consists of using the force measured from digits 3-5 to control the position of an actuator. This mapping between finger force, and the position of the actuator is then scaled by a gain in order to reduce the amount of force necessary from the user to control the actuator.

6.5. STUDY PARTICIPANTS

To pilot test the IGRIP 10 unimpaired subjects (4 Males, 6 females, age: 39.1 +/- 13.8 SD) were recruited for participation in the study. This study was approved by the University of California Institutional Review Board (IRB), and all study participants gave their consent prior to participating in the study.

6.6. RATIONAL FOR EXPERIMENT

The IGRIP was initially tested with unimpaired people in a “prosthetic finger” mode. In this mode the soft actuator which is attached to the exoskeleton replaces the index finger of the users hand. Using the exoskeleton in this mode provided several key insights that form the rationale for this study. The first, was that while using the exoskeleton in prosthetic finger mode it is similar to having a deafferented index finger. The user is no longer receiving tactile information from the index finger although the thumb is still providing complete information to the user. The second observation was that while in this mode the user loses microslip information from the index finger. But although that information is gone they still possess grip force control, and object position information in addition to microslip information from the thumb. The third observation is that the artificial finger has a fixed index finger impedance which is predetermined by the position of the soft actuator. Finally, we have an inability to apply forces in a desired direction through the object. Of these observations we chose to focus on the third observation: the artificial finger has a fixed index finger impedance. We hypothesized that the artificial finger impedance offered by the soft actuator may match the normal impedance of the thumb at some level of grip force. If we are able to determine this level of grip force, then if we hold an object at the correct weight, we would have a "matched situation" where the fake index finger impedance equals the normal index finger impedance. In that case, we would then have a deafferented index finger that cannot modulate its grip force magnitude or direction. If we assume that the sensory information from the thumb is sufficient for control and we match impedance with the fake finger, then ultimately what we are altering is the ability to modulate grip force. This raises the question then “Is it the loss of the ability to modulate grip force that causes the feelings of decreased control and sensation?”. Additionally, recent work has shown that intact finger perception helps facilitate motor learning [35]. Thus a second question was “Does a control strategy based on grip force modulation help facilitate motor learning?”.

6.7. IMPEDANCE MEASUREMENT OF SOFT ACTUATOR

To measure the local impedance of the soft actuator a paper cup with similar dimensions as the cup that will be used in the experiment was instrumented with a force sensor. The rest position of the soft actuator was set such that the soft actuator was 90%

flexed. This was also the same starting position of the mechanism that individuals used the exoskeleton in during the study. The instrumented cup was then placed on a table in a position that enabled it to be in contact with the mechanism. This was done so that we could measure the contact force between the mechanism and the object. The initial force was recorded for 30 seconds at the given diameter of the cup. At the end of the 30 second period we recorded the average force of the 30 second session. Afterwards we varied the effected diameter of the grasped object. This was done by simply sliding the object toward, and away from the mechanism along a line defined by the line between the grasp contact of the actuator and the grasp contact of the thumb. The effective diameter of the cup ranged from 2.18 in. to 2.58 in. with the diameter of the cup used in the experiment being 2.38 in.. This impedance measurement was performed a total of five times, at each of the different diameters and then the average of the force recorded at diameter was taken. The measured force was then plot against the diameter of the cup, and a regression line was fit to this data. The slope of the regression line here represented the impedance of the soft actuator. The impedance that was calculated using this method was then compared to impedance values calculated in another study in order to determine the appropriate grip force, and corresponding weight of the object necessary for the determined level of grip force [177] (Fig. 32). The impedance was also calculated for other positions of the actuator as well (Fig. 33).

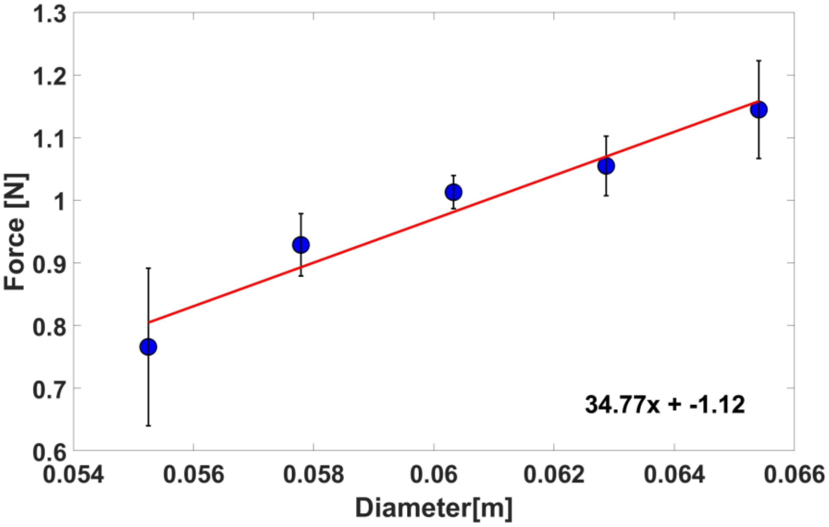

Figure 32. Impedance plot when actuator is 90% flexed. Measured force is on the y axis while the x axis represents the effective diameter of the cup used in the impedance calculation. Force was averaged over a 30 second period, at each diameter. The test was then repeated four additional times, and then the average of those five total trials was taken and used as the force at the given diameter. Afterwards linear regression analysis was performed. The slope of this regression line represents the impedance of the soft actuator.

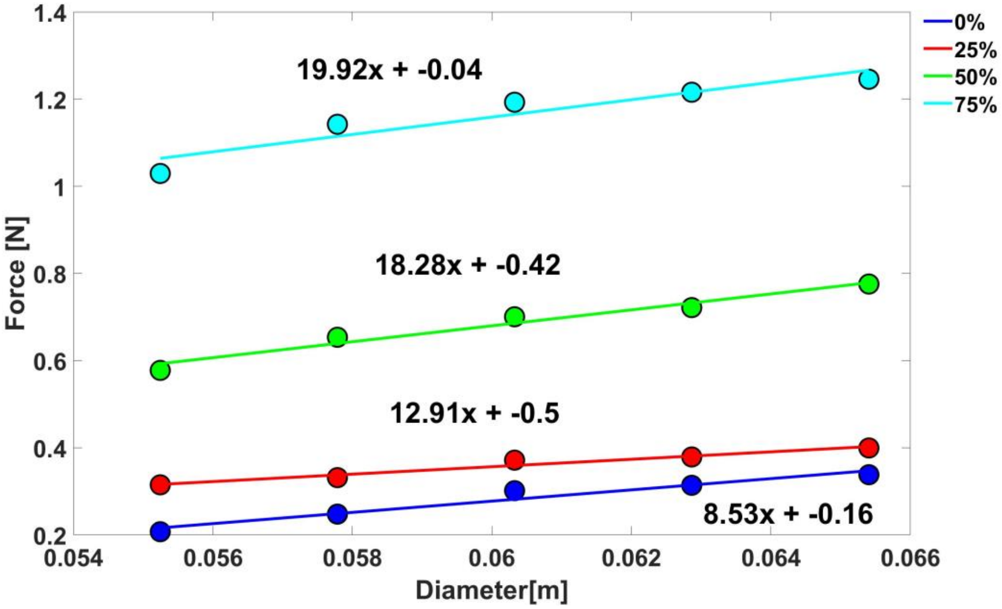

Figure 33. Impedance plot for multiple positions of the actuator. Measured force is on the y axis while the x axis represents the effective diameter of the cup used in the impedance calculation. The same methodology used to calculate the impedance when the actuator was 90% flexed was also used to calculate the impedance for these additional configurations. It should be noted that here 0% means that the actuator is not flexed at all.

6.8. EXPERIMENTAL PROCEDURE

Subjects were asked to grasp a paper cup using a pinch grip in three different conditions. During each condition subjects were asked to lift the cup up and down in an oscillating motion between two end points that were marked on a ruler that stood vertically. Subjects were asked to perform this oscillating motion for 30 seconds with the goal of trying to perform as many vertical up – down motions with in the allotted time. At the end of each condition subjects were told the number of movements that they were able to achieve in the 30 second time frame, and their frequency of movement was recorded. Here, the frequency of movement represents the total number of movements achieved divided by 30 seconds. In total subjects performed these 30 second sets 10 times with the goal of trying to increase the number of repetitions they achieved in the subsequent trials. Participants were also given a 10 second break between each trial, and a 30 second break when switching between conditions. In the first condition subjects used their own index finger and thumb to perform the pinch grip. In the second condition subjects were asked to perform the pinch grip using their thumb and the soft actuator, however, the soft actuator was powered off meaning that squeezing on the force transducer would not cause the soft actuator to flex any further than it’s starting position. In condition two the soft actuator was also positioned such that is was 90% flexed. In the third condition subjects again used the soft actuator and their thumb to pick up the cup, however the soft actuator was powered on. In this conditions when subjects squeezed on the force transducer this would cause the actuator to flex from 90% to 100% thus allowing subjects to modulate their grip force in this condition. Additionally, three days later subjects were retested, and performed the same grip-lift-move task. Except in this follow-up they only performed the task with the exoskeleton powered off, and exoskeleton powered on conditions. For both the baseline test, and the follow-up test the order in which subjects experienced the conditions was randomized.

6.9. RESULTS

The frequency at which people were able to move the cup was significantly greater when individuals were able to modulate their grip force with the exoskeleton (Exo - FM) in comparison to when individuals could not modulate their grip force (Exo – No FM). (p < .01, Two-tailed paired t-test) (Fig. 34).

Figure 34. Learning curves generated from use of the IGRIP exoskeleton. The No Exo – Hands Only condition represents when individuals performed the study using their own index finger and thumb. The Exo – No FM condition is representative of when subjects were wearing the exoskeleton however the actuator was powered off, and subjects could not control their grip force while the Exo – FM condition is the opposite of this (i.e. subjects could modulate their grip force).

Additionally, when individuals were able to modulate their grip force they increased the frequency at which they were able to move the object by 30 % starting on average with an initial frequency of 1.2 Hz and finishing with an average frequency of 1.75 Hz. by the 10th trial (Fig 34). However, this observation was not statistically significant although it was trending towards significance (p = 0.08). Similar trends were also seen when looking at the follow-up data, with subjects increasing their frequency from 1.2 Hz in the first trial to 1.6 Hz by the 10th trial when they were able to modulate their grip force (Fig. 35).

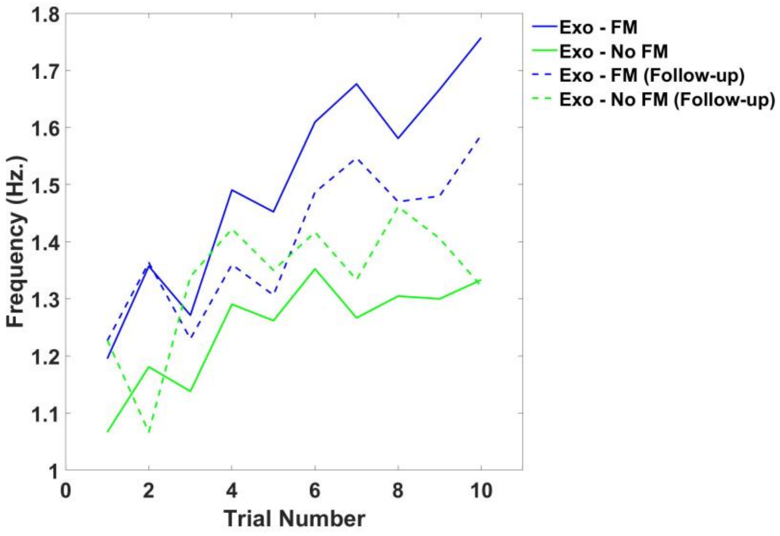

Figure 35. A follow up test was performed three days after the initial testing. However it should be noted that only six subjects were available for initial testing. During the follow – up testing only the conditions using the exoskeleton were performed by the subjects.

However, when comparing the achieved frequencies from the follow-up visit to the frequencies achieved at baseline, the follow-up frequencies were lower . Suggesting that retention of the control strategy is low although this likely could be due to the small sample size (only six subjects were available for follow-up testing). People also became more efficient at using the strategy gradually decreasing the amount of force used over time (p

= .03, Linear Regression Analysis) (Fig. 36). But, there was not a trend in the standard deviation of the force people used suggesting that people did not learn how to perform "quick" grip force modulation (in response to inertia and slips) (Fig. 37).

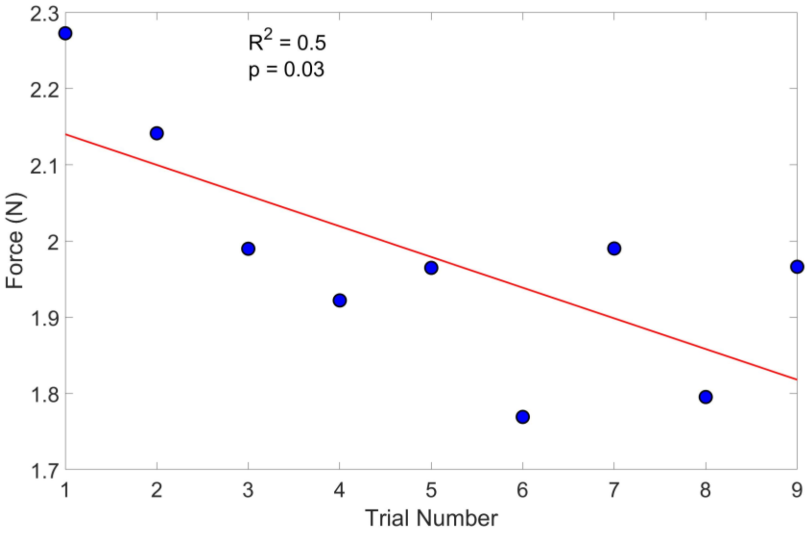

Figure 36. Force in the figure above is representative of the average force for all 10 subjects that participated in the study.

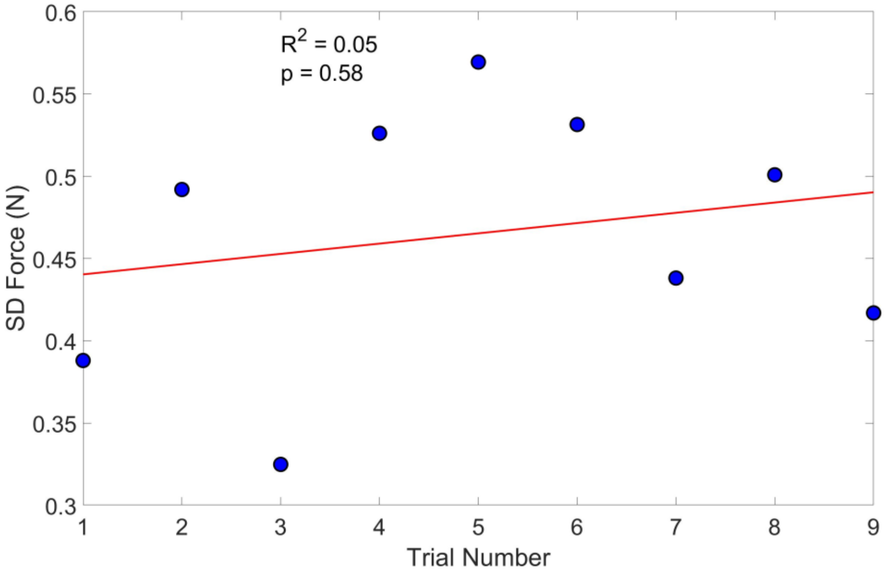

Figure 37. The standard deviation in the figure above is representative of the average standard deviation for all 10 subjects that participated in the study

6.10. DISCUSSION

Currently, hand exoskeleton control is primarily dominated by two control strategies; switch based control, and sEMG. Switch based control is simple to implement however, lacks intuitiveness as it requires the use of the unimpaired limb to initiate movement of the impaired limb. The use of sEMG has produced sub-optimal results, with commercially available options such as the MyoPro Hand Orthosis implementing such a strategy. The RFC is a potential alternative control strategy that has been shown to be intuitive to learn in both a rigid hand exoskeleton [175], and in the current study with the IGRIP a soft hand exoskeleton. Further, measuring the residual force in tact in the hand after stroke represents a direct way to control a hand exoskeleton that is simple to implement into the design of a hand exoskeleton. However, the same working principle that makes the control strategy intuitive could also be a limitation. In the present study individuals noted that at times they felt that it was fatiguing to continually have to press on the force transducer to control the force of the soft actuator. This observation is not specific to the IGRIP exoskeleton, and has also been seen in the prosthetic literature with terminal hooks. In the prosthetic literature there are two ways to control a prosthetic hook voluntary opening, and voluntary closing. Voluntary closing allows the user to control closing the terminal hook while a spring maintains the open position of the hook while the voluntary opening strategy is the opposite (i.e. a spring is responsible for keeping the hook close, while the user has control over opening the hook). In a study comparing these two strategies with 27 unimpaired participants, and 5 amputees a similar observation was made with subjects stating that continually trying to maintain the force while holding the object can be fatiguing, and somewhat cognitively demanding. It was also shown that depending upon the task users preferred one control strategy over the other. Specifically for tasks that required more control over the force the voluntary closing strategy was preferred, while for tasks that required simultaneous movement the voluntary opening strategy was preferred. Interestingly, participants in that study also noted that the optimal device would incorporate both strategies, and enable users to switch been either strategy [178]. Thus, in future work with the IGRIP exoskeleton will explore if the continuous working of the fingers has a therapeutic effect in stroke survivors, if there is a need to include an additional strategy such as voluntary opening, and if stroke survivors are also able to intuitive learn the strategy.

CHAPTER 7. CONCLUSIONS AND MAIN CONTRIBUTIONS

In the beginning of this dissertation, we identified non-intuitive control strategies, overly-bulky devices, lack of consideration of sensory deficits, and lack of understanding of usership needs and patterns as bottlenecks for wearable robotic device development after stroke. Through the design work and experiments detailed in this dissertation, we made advances in: Usership Patterns of Wearable Sensor Technology ,Sensory and Motor Control of the Hand after Stroke, and Mechanical Design and Control of Hand Exoskeletons. We detail these advances below as well as discuss future directions of research.

7.1. USERSHIP PATTERNS OF REHABILITATION TECHNOLOGY

There exists very few robotic devices that have been developed that are viable for use in either the home setting or the clinical setting. This makes studying how patients would use devices in unsupervised settings challenging. Wearable sensing technology represents an opportunity to study these patterns, and gain a better understanding of what potential factors we need to account for when designing robotic technologies for robotic therapy solutions. Furthermore, there have been very few studies that have attempted to look at usership patterns, with the few studies that have using subjective scales such as the system usability scale [181]. Our lab has developed the MusicGlove device, a wearable grip sensor that is unobtrusive, simple to use, and available commercially. The device is able to be used in the home setting, but also provides quantitative data on device use. The combination of its usability, and data collection abilities provided us with the opportunity to study the usership patterns of a rehabilitation device in the home setting, and has allowed us to perform one of the first usership studies of this magnitude. Studying the usership patterns of the device provided several new insights to the field of rehabilitation for both the development of assistive devices, and for the improvement of rehabilitation therapy paradigms. Regarding, the development of assistive devices it was revealed that people with stroke stop using devices for a wide variety of reasons, producing failure curves that follow a Weibull distribution, a distribution that is commonly used to model machine part failure. Second, it was shown that only 14% of individuals screened for participation in the study qualified for a sensor based approach. Suggesting that there is a growing need for the development of devices that can offer assistance to the user. For the development and improvement of rehabilitation therapy paradigms we have shown that people like to train at high success levels, and when given the ability to adjust challenge levels will challenge themselves in a logical way consistent with motor learning theory. A common concern of therapists is whether or not patients performing rehabilitation in the home setting will challenge themselves appropriately, or if they will perform movements that could be detrimental. Here we have shown that people have an intuition about how to appropriately challenge themselves. Additionally, we showed that people infrequently make challenges (~30%) of the time, and at times modulated difficulty in a non-intuitive way. This is contrary to most adaptive algorithms that have been developed which try to modulate parameters after every trial. Thus if we are to make adaptive algorithms more “humanistic” this work would suggest changing the frequency at which adaptations occur, and modulating difficulty in a stochastic manner.

7.2. SENSORY AND MOTOR FUNCTION OF THE HAND AFTER STROKE: IMPLICATIONS FOR MECHANICAL DESIGN AND CONTROL OF HAND EXOSKELETONS

In Chapter 4 of this dissertation we described the current body of knowledge on sensory deficits after stroke. It is well understood that sensory feedback plays an important role in the execution of tasks. But, previous attempts to assess sensory deficits however, were coarse and had a number of limitations that made interpretation of results obtained by their use difficult. This led to a robotic revolution of sorts, with there being a substantial increase in the number of robotic devices developed to assess sensory deficits such as proprioception or tactile sensation over the last decade. These robotic devices are able to provide quantitative data about sensory deficits in a rigorous way. However, there still remains a key fundamental gap in knowledge. How do these new robotic measures correlate to motor function? After reviewing the proprioception assessment literature we argue that there are a number of devices that have been developed to assess sensory deficits such as proprioception, and there are even a few devices that have developed to train proprioception but there are very few studies that have examined how these new robotic measures relate to sensory deficits. Concerning, proprioception we have only found one such study that has developed a robotic measure of proprioception, and examined it’s correlation with motor function. But that study focused on the relationship between proprioception of the arm, and clinical measures of motor function. When focusing on the hand alone we were not able to find any studies that showed a correlation between proprioception of the hand specifically finger proprioception measured robotically and clinical assessments of motor function. In previous work our lab has developed the FINGER exoskeleton, and validated the crisscross method as a way to measure one aspect of hand proprioception: finger position sensing [142]. That work also showed that individuals who benefitted most from robotic therapy possessed intact finger position sensing [179], [180]. We have, extended this work even further in this dissertation and shown that finger position sensing measured robotically is correlated to motor function of the hand after stroke. Further, we also showed that compared to tactile sensing finger position sensing seems to have greater importance on hand function. These observations have implications on the way that we design hand exoskeletons in the future. Namely, if we are to increase the therapeutic benefit that hand exoskeletons can provide, we need to develop devices that can promote, re-train, and challenge finger position sensing.

In chapter 3 of this dissertation we discussed common motor impairments that impact hand function after stroke such as spasticity, flexor hypertonicity, lack of finger individuation, and flaccid paresis. These impairments conspire together to severely limit hand function, and often cause individuals to have weakened grip strength, and an inability to perform dexterous movements. Additionally, individuals with a stroke often have issues with force control. Several rehabilitation researchers have pointed to aspects of force control that are impaired such as asymmetrical force production in the hands, , greater force variability during both unimanual and bimanual isometric force control tasks , and there an increase in task performance error during isometric force control tasks. But one aspect of force control that appears to be overlooked is the ability to modulate grip force at certain force levels. Our lab as well as others have shown that when the Maximum Voluntary Contraction is less than 30% individuals retain the ability to control their isometric flexion forces. In this dissertation we have examined how this ability to control isometric flexion forces compares to other aspects of hand function such as dexterity, and grip strength. This test revealed that isometric flexion force control is much more preserved than dexterity or grip strength in the hand after stroke. From this observation we developed a novel force control strategy: residual grip force control (RFC). We have shown that the RFC strategy offers intuitive control of a hand exoskeleton. This is evidenced by the ability of individuals to improve their performance using the strategy with both a conventional hard exoskeleton, and a soft hand exoskeleton.

7.3. MECHANICAL DESIGN

In Chapter 2 of this dissertation we showed that although overly-bulky robotics are a challenge, there indeed is a need for assistive robotics, as only 14% of stroke patients can qualify for a purely sensing-based approach. Many hand exoskeletons that are developed focus on facilitating a power grip. However, this design can often lead to the development of bulky and obtrusive devices. In Chapter 5 of this dissertation we have shown that using a pinch grip alone you can achieve 80% of normal hand function. This observation is also consistent with what other researchers in the field have shown. This suggests that we can improve the bulkiness of the device and thus the mechanical design of devices by potentially focusing on a pinch grip which has a reduced number of degrees-of-freedom. Hand exoskeleton devices in past studies have been developed mainly using links, tendons or pneumatically driven mechanisms. Traditional rigid links can transmit bi-direction forces unlike tendon mechanisms which are also commonly used in hand exoskeleton designs. But linkage exoskeletons inherently suffer from size, weight, and backlash and play in the mechanical linkage. Tendon mechanisms are also typically employed because of their compactness, but tendon mechanisms typically can only transmit forces uni-directionally, making the mechanism more complex if one were to attempt to transmit bi-directional forces. Pneumatically driven mechanisms are another form of actuation often used in the design of hand exoskeletons. Pneumatically driven exoskeletons have the advantage of good power to weight ratios, and can be directly integrated in gloves for example. Pneumatic devices however, often require the use of many auxiliary components such as pumps which increase the bulk of the system. Taking this into account, we developed a novel soft actuator that can replicate finger-like compliance and force properties in a lightweight practice. Some of the other advantages of the mechanism are: no backlash, no lubrication required, and freedom from machine noise and abrasion powder.

7.4. DIRECTIONS FOR FUTURE RESEARCH

There are several different directions that can be taken with the IGRIP exoskeleton. The first line of research could focus on validating if the residual force control strategy is indeed intuitive for persons with stroke to learn. In the present line of work we have shown that unimpaired individuals are able to learn how to effectively use the control strategy but that does not imply that persons with stroke will also be able to learn how to use the study. Further we will need to evaluate if there are any potential therapeutic effects of using the residual force control strategy on motor function. Another line of work could focus on improving the design of the actuator used in the exoskeleton. Currently the forces that are provided by the exoskeleton are relatively small, limiting the number of objects that a person could interact with when using the device. Additionally, the softness of the actuator inhibits the actuator from being placed on the dorsal side of the hand. In the current setup the soft actuator needs to be place on the lateral side of the index finger in order to move the finger. Thus future work could explore using different materials in place of the original soft materials. As finite element analysis showed that by in increasing the stiffness of the material the output force of the actuator increases as well. One other line of research would be the exploration of the voluntary opening strategy. Essentially this would mean that pushing on the force sensor would cause the fingers to extend instead of flex. This potentially could have interesting therapeutic benefits as although it would be counter intuitive (flexion leads to extension) it provides a way to train finger individuation.

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