A Soft Robotic Exomusculature Glove with Integrated sEMG Sensing for Hand Rehabilitation

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Abstract—**Stroke affects 750,000 people annually, and 80% of stroke survivors are left with weakened limbs and hands. Repetitive hand movement is often used as a rehabilitation technique in order to regain hand movement and strength. In order to facilitate this rehabilitation, a robotic glove was designed to aid in the movement and coordination of gripping exercises. This glove utilizes a cable system to open and close a patients hand. The cables are actuated by servomotors, mounted in a backpack weighing 13.2lbs including battery power sources. The glove can be controlled in terms of finger position and grip force through switch interface, software program, or surface myoelectric (sEMG) signal. The primary control modes of the system provide: active assistance, active resistance and a preprogrammed mode. This project developed a working prototype of the rehabilitative robotic glove which actuates the fingers over a full range of motion across one degree-of-freedom, and is capable of generating a maximum 15N grip force.**

I. INTRODUCTION

Physical disability after a stroke is characterized by of loss of dexterity and strength, to the afflicted side of the body [1]. This loss of strength is due to lost motor function and coordination of muscle recruitment. That is to say the brain is injured but the muscles and nerves are still functional. Repetitive motion exercise helps to re-map the motor function in the brain; much like a child learning to walk for the first time, so too can a person re-learn how to move their body again.

Rehabilitation of strength in the paretic hand is improved via repetitive controlled motion of the hand [2]. Occupational therapy for stroke rehabilitation involves the repetition of tasks that aid in accomplishing tasks of daily living. In occupational therapy this involves various tasks and games that build up strength and dexterity. These activities include exercises such as picking up objects and placing them elsewhere, dressing, eating; and other similar tasks that require opening and closing the hand, and manipulating objects in coordination. Moreover the level of difficulty of each task depends on the patients level of functionality and the occupational therapists assessment [3]. Occupational therapy is tailored to the users needs and ability and as their functionality improves, the level of therapy increases. Occupational therapy occurs largely in hospital or clinical settings, but can migrate toward home therapy. Home therapy incorporates the recovery of daily-living-activity functions as well as incorporating environmental adjustment at home and can help improve efficacy. The ability to perform rehabilitation at home is beneficial for functional and psychological performance, and for independence [4].

In general, factors that improve recovery after a stroke include early intervention, repetition, and motivation. Patients who are more active and persistent in their rehabilitation, are better able to regain more function. During rehabilitation the patient may use exercise equipment or other devices that provide assistance and resistance in therapy. Exercising the recovering area is beneficial in recovery, as building strength increases function [5]. Assistive intervention allows for the patient to regain function in early stages of recovery. Resistive exercises allow for the patient at a higher functional level to strengthen their body. In some cases a combination of assistance and resistance can be used in a rehabilitation sessions in order to develop various functions.

Modern developments in biomedical technologies have led to the use of robotic systems in physical assistance and rehabilitation. Companies like iWalk, have been working on a number of different prosthetics. The PowerFoot One is an advanced complete ankle-and-foot prosthesis. The device takes measurements thousands of times a second to accurately reproduce the movement of a fully functional human foot. Not only does this device mimic human foot movement, but it is one of the first devices that uses its own movement to power itself; this allows for the device to become more compact and portable. The Rheo Knee developed in Iceland is another example of advanced robotic prosthetics. This design is innovative because it tracks the users gait and adapts its walking algorithm to better suit the user. The DEKA a company developed the “Luke Arm” . This commonly publicized device is a prosthetic aimed toward individuals that are missing an upper limb. This device is designed to provide a person with a partially articulated robotic arm that uses foot pads to control and move it [6].

Current devices available for hand rehabilitation are composed of either glove-like orthotics or larger robotic machines. The glove-like devices tend to be unpowered orthotics that are portable, providing only support and coordination. Unlike passive orthotic devices, exoprosthetic devices are able to achieve some sort of actuated movement. The robotic machines tend to have sensors and motors for feedback and assistance, but are limited to desktop use.The Tokyo University of Agriculture and Technology is developing an exo-suit to help the elderly and people with disabilities [7]. Ueki et al. developed a robot

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which holds a human hand and manipulates it in various degrees of freedom. This system is a desktop unit with an array of motors and joints for each digit. The actuators provide active manipulation of all digits for both flexion and extension, as well as wrist rotation. The robot is controlled by a master-slave system in which a control glove is worn on the healthy hand and its motions are reflected onto the arm undergoing rehabilitation. [8] Compact devices that fit on existing limbs, like Myomos mPower100 elbow system, aim toward home use. These technologies highlight the possibilities of control, portability, and feedback in prosthetic and orthotic devices. Robotic devices allow for more efficient and precise assisted therapy. A 2011 study comparing robotic and standard hand therapies for recovering stroke patients, found that those using the robotic system recovered more effectively and with less injury [9]. Another example is by an Jugenheimer who described “A Robot for Hand Rehabilitation”. The work includes many designs and considerations as well as significant background research for a lot of the fine motor functions and degrees of freedom of the hand [10] , thus lending way to more articulated designs and functions. These systems allow for guided motion in therapy, which can decrease injury and increase recovery efficiency.

These robotic technologies can take on more compact forms such as gloves. A glove design allows for a wearable device that is intuitive to use. A patent for a Hand Rehabilitation Glove states a design wherein the patient wears a glove that is comprised of pockets of a compressible fluid to exercise individual fingers. The glove is intended to aid in therapy and to minimize the stresses on the hand, fingers, and joints during therapy [11]. The complexity of these robotic systems, as well as the level of feedback and interaction can vary by design. One of the many current forms of rehabilitation for the hand includes a device called the “Hand Tutor.” The device is a glove that tracks the users hand motions and allows them to play games during hand exercises. This gives feedback to the patient and allows them to improve the motor function of their hand [12]. A wearable design such as this is suited for use in everyday life, so that rehabilitation becomes concurrent with daily tasks. The SaeboFlex by Saebo is an unpowered wrist-hand-finger orthotic being marketed and used in therapy for patients that need to regain muscle tone in the hand. This device consists of adjustable springs used to provide resistance and stability to the fingers during rehab exercises. A group of engineering undergraduates from Columbia created the J-glove which uses cables to provide tension during extension [13]. The cables ran trough tension sensors and were driven by motors. The motion of extension via cable tension could also potentially be utilized for flexion.

This paper describes the development of a cable drive soft robotic glove intended for stroke rehabilitation. The glove can independently actuate all five fingers using position or force control. Surface EMG (sEMG) using custom electrodes and interfaces circuitry are integrated into the forearm sleeve for detecting user intent and controlling the device. The actuation and control system is battery powered and fully self contained in a portable light weight backpack. We describe the design and testing of the prototype device.

II. SYSTEM OVERVIEW

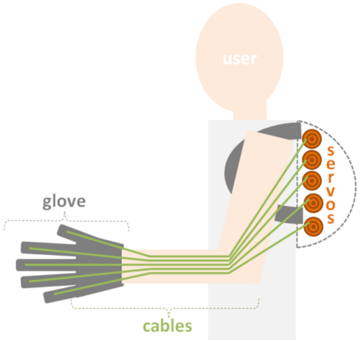

Figure 1: *The concept was to have a glove that could apply tensile forces in order to aid finger extension and flexion . The servomotors could be worn in a backpack with the electronics while the glove is attached to actuated cables.*

A. Mechanical Subsystem

The glove itself is made out of a spandex material, due to its flexible yet supportive form-fitting weave. The cable guides are 3D printed plastic pieces that hold the lines centered to each finger. The Kevlar cable was chosen not only for its high tensile strength but also for its flexibility to contour to a users hand. The Kevlar thread is fed through polyethylene surgical tubing, forming a Bowden cable system to allow for the servomotors to be a considerable distance away from the physical glove, thus relieving any unneeded weight on the users forearm or hand. The Bowden cable system runs along the length of the arm, up around the shoulder and terminates at a backpack servo case. It is here that the inner Kevlar line is wound around a custom-made spool. The flexion and extension cables from one digit are both attached to one spool. Each spool was sized to take up the needed amount of line to move the individual finger it controls. The spools are mounted onto five servos one for each digit. The servomotors are capable of being position and torque controlled. The system is able to control each finger independently and move each digit to any position between open and closed grip, while regulating grip force through motor current.

B. Control Model

The glove has three different control modes: switch, programmed position, and EMG. While in the switch control mode the glove is controlled by a three-position switch that opens, closes, and moves the fingers to an initial position all based on the position of the switch. The programmed position mode allows a moderator to preprogram the glove to actuate between predetermined positions. This functionality would be ideal for a therapist creating an exercise regimen for their patient. Finally the EMG mode allows for the user to control the glove based on their myoelectric signals. Within this mode, the system has the ability to provide active resistance or assistance. Active resistance makes the glove provide a resistive force opposing the opening or closing of the hand, fighting against the users intended movement whilst providing stability. Active assistance aids the user in their intended movement, by supplying forces in the same direction. .

C. Electromyography

During a gripping motion, the fingers are predominantly moved by large muscles in the forearm. When the fist is opened, the extensor digitorum pulls back (extends) the fingers. And during the flexion of the fingers to close the hand, the flexor digitorum profundus provides much of the necessary tension. These muscles are large and relatively close to the skin. Surface electrodes are then capable of detecting the EMG from skin contact atop these muscle groups.

An affordable surface electrode-amplifier for obtaining an electromyogram and an accompanying signal processing circuit were designed at Worcester Polytechnic Institute. The design includes two circular stainless steel heads connected to an instrumentation amplifier circuit all packaged within an epoxy shell. The amplification circuit consists of an instrumentation amplifier and differentially amplifies the signal by a gain of 20 [14].

III. METHODS

The design consists of a glove which actuates the fingers in flexion and extension, via cable tension. The cables attach to spools on servomotors in a backpack; this connection is made possible through the use of a Bowden cable system which allows the cables to slide within tubes and the force of the servomotors to be translated to the fingers. The system is controlled by a microcontroller, also in the backpack. The microcontroller offers three control options: switch mode, programmed mode, and EMG mode. The EMG mode uses electrodes on the forearm to provide control signals from the flexor and extensor muscles of the fingers.

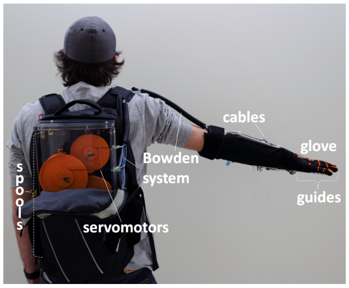

Figure 2: *Display of the system design.*

A. Mechanical Subsystem

1) Overview: Mechanically, the design encompassed a subsystem which includes: a glove, cables, and actuators (see Figure 7). This mechanical subsystem allows for an effective, compact, and modular approach to a robotic stroke rehabilitation glove. In using this device with someone with limited hand movement from an injury or stroke, the design tried to keep as much weight and components off the hand and forearm. Servomotors are housed in a backpack that the user wears. The servomotors spin custom made spools with radii that are sized based on the amount of cable needed to be pulled to extend and flex each finger individually. The cables that the spools wind up, extend down to the forearm through a Bowden cable system. The cables are then fed up through a rigid guide mounted on the forearm. The forearm mount is the connection between the cables from the glove and the cables from the servomotors. By having two separate cables the tension can be adjusted for different users at this junction by adjusting the cable length at the forearm juntion with the custom tensioners. The cables on the hand run parallel to the long axis of the forearm. The cables are held in place by custom guide pieces attached to the glove. This system not only allows for modularity, but is also a simplistic and effective method of actuation of the hand.

2) Glove Design: The main design requirements for the glove was to keep it low profile, comfortable, and easy for someone with limited hand mobility to use. The material of the glove itself needed to be form fitting to the hand in order for the actuation to be effective. Keeping the cable lines tethered to both the palm and the dorsal side of the hand using the cable guides allows for a low profile design. The use of a cable system also permits for there to be no local actuator devices near the hand, keeping weight off the arm. The type of glove selected was originally designed to be a glove liner and is already made of slim and comfortable material. The material of the glove is a spandex, moisture-wicked material (Seirus Innovations, Thermax Deluxe Glove Liner).

3) Cable Guides: The cable guides used in the first model were prototyped from PVC pipes and safety pins. Using the overall shape of these, low-profile and effective cable guides were created. The cable guide system were rapid-prototyped parts, spread into three different types: fingertip, phalanx and palmar.

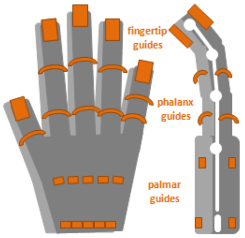

Figure 3: *Cable guide diagram. Three types of guides: fingertip, phalanx, and palmar. Guides were placed in on either side of each joint in the finger in order to allow comfortable bending.*

The fingertip piece is placed onto the tip of the glove at each finger to create a fixed point for the cable to be attached to the glove. This is the only point on the glove that the cable is rigidly attached to. Attaching the cable at the fingertip maximizes the leverage on the finger. The phalanx guides are half-circle pieces that are placed on the intermediate and proximal phalanges, between the knuckles (only intermediate for the thumb). The guides are glued at the midpoint of each phalanx of the finger in order to distribute the forces along the finger and to align the cable tension along the axis of flexion/extension. The guides have to be centered along this axis in order to prevent adduction or abduction(the spreading or bringing together) of the fingers. These pieces are meant to tether the cables as close to the finger as possible in order to allow the maximum range of motion and force to be translated along the finger. The palmar cable guides are smaller pieces mounted on the dorsal side of the hand and the palm to help keep the cables taught past the wrist, as seen below in Figure4.

Figure 4: *Cable guide assembly on glove. Cable lines run centered down the middle of the long axis of each digit and are attached rigidly at the fingertips. Note fingertip, phalanx, and palmar guides.*

4) Bowden Cables: In order to minimize the number of parts on the arm, and to allow more options in terms of actuation, the team studied alternative methods to transfer cable movement over a distance. Looking back at some preexisting prosthetic devices it was found that Bowden cable systems are often used. This system works the same way that a bicycle brake cable works, where force is remotely transferred from handlebar to wheel. The cable is able to slide inside the sleeve and transfer the displacement and tension; shielding the cables from the backpack to the forearm. Polyethylene 0.11 inch diameter surgical tubing was used as the plastic sleeve.

5) Spools and Servos: The Kevlar lines for both the flexor and extensor are attached to the same spool. This can be done because the flexion and extension motion is coupled. Putting them on different spools and servomotors would double the total number of spools and servos needed, as well as requiring the servomotors to be in synchronized motion. Having both lines on a single spool simplifies the system and removes a potential mode of failure.

Various cam shapes were tried to achieve a single layer spool that allowed both the tensor and extensor cable to be wound up simultaneously, but in the end two stacked circles of differing radii for each finger proved to be the best solution. So, as the spools rotate they take up slack in one direction while providing tension on the other side. Each spool was designed to be able to reel a specific amount of line to move each individual finger. The amount of required displacement was determined by measuring the displacement of Kevlar line that occurred when the hand went from an open position to a closed position. Measurements were taken and an average was taken and used for the calculation of spool diameter for each finger. This calculation for the spool diameters was done using the arc length equation:

$$s = r\Theta \tag{1}$$

Where s is the displacement of Kevlar line for a specific finger, r is the radius of the spool for the specific finger and θ is the degree revolution of the servo motor. For the current system the spool sizes were determined off the hand sizes of the team members. The spools are designed in such a way that after a few descreate measuremetns based off the useres hand custom spools can be generated. The final rendition of the spools were rapid-prototyped parts made of solid a single piece which were more sturdy and reliable 5. These pieces were attached to the servomotors and were effectively tested.

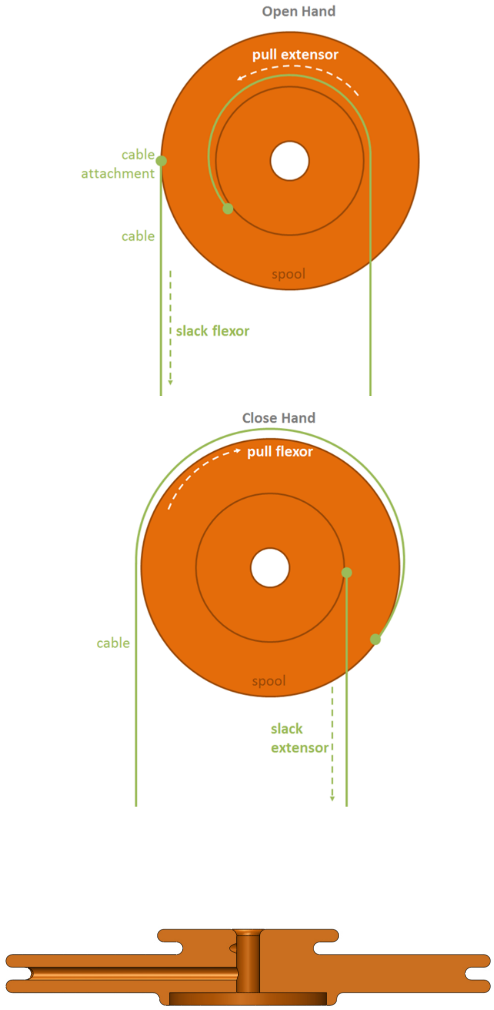

Figure 5: *(Bottom)Two-Layered spool design cross-section. Top diameter for flexion, bottom diameter for extension of the fingers. (Top)The top layer of the spools pulls the extensors for opening the hand. (Middle)The bottom layer of the spools pulls the flexor for closing the hand.*

The servomotors used (HiTec 5465 series) were able to rotate from 0° to 200° due to internal locking and so the spool diameters were calculated based on this arc movement. Five servomotors were used, one for each finger. Each servomotor had a custom two-layered spool, with each layer being sized the right diameter to move each corresponding finger across the 200° arc, for both flexion and extension. The position was controlled by pulse-width-modulation and the force by current limiting. This allowed for each finger to be controlled in both position and output force independently.

B. Electrical Subsystem

A custom circuit board was designed to interface with a microprocessor board so that the glove could be operated. The circuit seen in Figure 6 consists of signal processing, servomotor control (current limiting), and power.

All of the op amps, digital potentiometers, and the 3-to-8 decoder had decoupling capacitors placed on the board next to them to help with noise. The signal conditioning portion of the board is powered by a battery pack that provides a 12V and a -12V rail. The servomotors and the MSP430 are powered by a separate +6V battery pack due to the amount of current they draw. A switch board, for user inputs, was also created and consists of: a toggle switch, a 3 switch dip switch, and a resistor dividing network that drops down the +12V so the digital inputs of the MSP430 would not be damaged.

1) EMG Control: EMG was collected from the forearm, specifically the extensor digitorum communis and the flexor digitorum profundis, as detailed in Figure 7. This was done by placing a bipolar surface electrode-amplifier on the skin above each muscle and a reference electrode on the bony part of the elbow. In effect there is an electrode-amplifier for the flexion signal, and an electrode-amplifier for the extension signal, and an electrode as a reference. Utilizing the power of the flexion and extension signals, the glove can be controlled based upon the users intent to flex/extend.

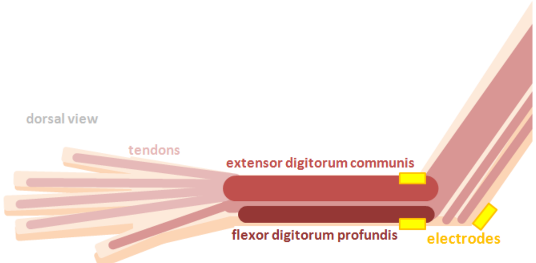

Figure 7: *Major hand flexor and extensor muscles where myoelectric control electrodes were placed.*

To keep out motion-based noise a signal conditioning circuit was implemented. The signal conditioning design was based on the work of Edward Clancy [15] and simplified for the purposes of this project. Two second-order Butterworth filters were designed, a high-pass and a low-pass. Originally a built-in gain of 10 on the low pass filter was used, but after several failed attempts, (where simulations worked but test circuits failed) it was decided to use two separate gain stages as well as the two filters. The high pass filter was designed to pass anything above 10Hz and the low pass filter anything below 750Hz. The digital conditioning circuit is diagramed in Figure 8.

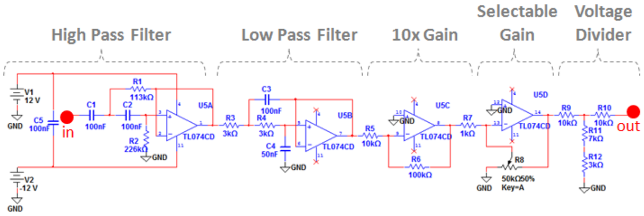

Figure 8: *Signal conditioning circuit diagram. The input is from the electrode-amplifiers and the output connects to the ADC on the microcontroller board.*

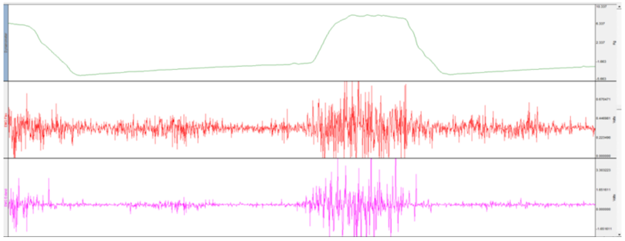

Figure 9: *EMG and force data taken using the electrodes made and the AcqKnowledge software. (top) is force in pounds,(middle) is the EMG flexion signal in volts,(bottom), is the EMG extension signal in volts*

Originally the conditioning circuit was designed so that it cascaded from the high pass filter, to low pass filter, to gain of 10, and then a to selectable gain (which uses a digital potentiometer to go from a gain of 1 to a gain of 50). However, based on our research [15] the cascade order was changed to: high pass filter, gain of 10, selectable gain, and then low pass filter. This change was made because having the low pass filter last produces the least amount of electronic noise. The last part of this circuit was a resistor network which shifted the 12V to -12V signal to be a 3.6V to 0V signal to match the range of the ADC on the MSP430.

2) EMG Use: Electrodes were utilized as a means to control the glove with the users own myoelectric signal (through EMG). This was implemented by placing two electrodes on the forearm, of the hand that was being actuated. One electrode was placed on the dorsal side of the forearm, on the bulky part of the extensor digitorum muscle, which mainly extends the fingers. The second electrode was placed on the flexor digitorum, on the ventral side of the arm. A third electrode was used as reference to cancel out the bodys background signal; this electrode was placed above the boney part of the elbow. And so EMG was obtained in two signals, one from the muscle which extends the fingers and one from the muscle that flexes the fingers. A control program was written such that if the hand was closed and the extending EMG reached a certain threshold, the servomotors would open the hand. And

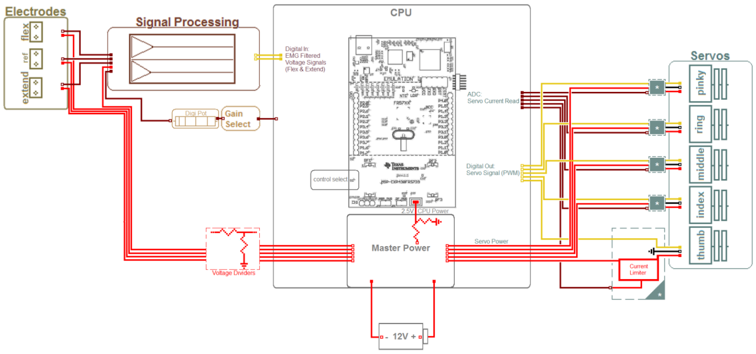

Figure 6: *System diagram with microcontroller in center. Electrodes connect to microcontroller through a signal conditioning circuit. Servomotors are current limited by the microcontroller. 12V power for system operation*

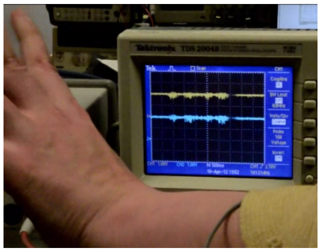

Figure 10: *EMG calibration: using oscilloscope the waveforms of the filtered myoelectric signal can be adjusted in terms of gain in order to make pulses visible. This signal is what the MSP430 would see.*

conversely if the hand was open and the flexing EMG reached a certain threshold, the servomotors would close the hand.

The EMG threshold depends on multiple factors. It is different from person to person depending on the natural power of their EMG; this can be accounted for with the selectable gain of the signal conditioning circuit. The threshold also is determined by how sensitive the control is programmed. There is a somewhat linear relationship in the power of the EMG signal and the amount of force that is being applied by the muscle. This relationship can be used with the current limiting circuit to not only actuate the servomotors, but to also dictate how much force should be applied.

IV. RESULTS&DISCUSSION

Overall, the system demonstrates a real working model of the design: a portable solution to hand rehabilitation. Moving foward such concerns such as system weight, grip strength and feasability will be addresed further and optimized int the next model of the sevice.

A. Grip Force

The maximum tension in the cables and the ensuing grip force were measured using a tension gauge. The maximum tensile force and grip force was 15N. This is enough force for a hand to pick up most common objects. The ability of the glove to grip was tested using a wooden mannequin hand with simple articulating joints as seen in Figure11.

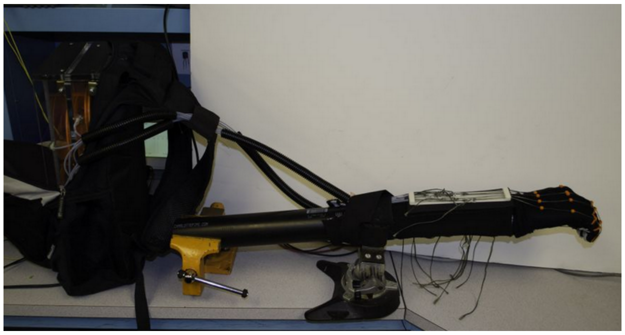

Figure 11: *Wooden mannequin grip verification test. The glove is equipped on a wooden hand with pin-jointed fingers. The servomotors were actuated to their open and close hand positions and the mannequin hand was flexed and extended.*

The mannequin hand proved to not have enough articulation to move naturally but was still actuated by the glove. Testing on human hands were successful. The users hand could be opened and closed involuntarily. When tensioned, the system allowed for optimal force transfer and supplied tension in flexion and extension. Moreover the cable flexion resulted in not only closing the users hand, but also providing grip strength.

B. Safety

Since this system would be used on a person, safety was a high concern. The main safety concerns that were considered were hyperextension and hyperflexion as well as electrical isolation. To prevent hyperextension and hyperflexion, the implementation of a quick-release sub-system was considered. This system creates a dynamic connection point between the cables coming off the hand and the cables that are being actuated from the servos. If a sudden need to release tension on the hand would arise, the user could pull a pin breaking the connection between the two thus releasing all tension on the hand. As the design of the system progressed, the implementation of the custom spools accomplished the same goal as the quick-release. Each spool is limited by the rotation of the servo and was designed to operate within these parameters. The only way this can be abused is if the user sets the servo position to closed and then puts their hand in the glove open and tensions it in the open position and then tries to open the glove further. The main safety concern when using electrodes is the possibility of a failure resulting in electrocution. However, the system bypasses this concern by using battery packs instead of connecting to an earth ground.

C. Electromyogram Control Calibration

The EMG threshold depends on multiple factors. It is different from person to person depending on the natural power of their EMG; this can be accounted for with the selectable gain of the signal conditioning circuit. The threshold also is determined by how sensitive the control is programmed. There is a somewhat linear relationship in the power of the EMG signal and the amount of force that is being applied by the muscle. This relationship can be used with the current limiting circuit to not only actuate the servomotors, but to also dictate how much force should be applied.

V. CONCLUSION

The rehabilitative robotic glove developed met the functional objectives of creating a wearable device that can be utilized for stroke rehabilitation. The device is capable of providing assistance in the flexing and extending of the users fingers. It can supply a 15N tensile force for this actuation and for grip strength. The cable and guides provide an effective means of delineating the actuation provided by the cables. The Bowden system allows for servomotors or in the future, other actuators, to be worn in a backpack. The spools and servomotors allowed for position and torque control sufficient to move each finger independently and with enough resolution for multiple positions. The control options (switch, program, and myoelectric signal) allow for stroke survivors to rehabilitate through different stages of recovery.

Having developed a solid first generation platform the current work on the system includes developing a more sophisticated sEMG array system, pressure and flex sensor integration to allow for real time feedback of the fingers potion and applied force to the surface of an object, and a more powerful and lighter actuation system.

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