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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, with the entire system portable and 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 an onboard interface, software program, or using myoelectric signals through integrated surface electromyography (sEMG) electrodes. The primary control modes of the system provide: active assistance for augmentation, active resistance for training, and preprogrammed or mimicked motions for repetitive motion motor learning. This project developed a working prototype of the rehabilitative robotic glove which actuates the each of the fingers on one hand over a full range of motion, 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 can be improved via repetitive controlled motion of the hand [2]. Occupational therapy for stroke rehabilitation often 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. *The system described in this work is capable of assisting in repetitive motion therapy, providing assistant, and providing reistance in a compact platform capable of being used in home therapy.*

Modern developments in biomedical technologies have led to the use of robotic systems in physical assistance and rehabilitation. Companies like iWalk (Bedford, MA), have been working on a number of different prosthetics. Their 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 (Ossur, Reykjavik, 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 company (Manchester, NH) developed the "Luke Arm", 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 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 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 the mPower100 elbow system (Myomo, Cambridge, MA) aim toward home use, but are typically rigid exoskeletons requiring careful alignment with the patient. These technologies highlight the possibilities of control, portability, and feedback in prosthetic and orthotic devices. Robotic devices can 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 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 leading the 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” describes 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 (Saebo Inc., Charlotte, NC) 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 students from Columbia created the “J-glove” which uses cables to provide tension during extension [13]. The cables ran through tension sensors and were driven by motors, and extension via cable tension could also potentially be utilized for flexion.

This paper describes the development of a cable driven soft robotic glove intended for stroke rehabilitation. The glove is worn without an exoskeleton, and can independently actuate all five fingers using position or force control. Surface EMG (sEMG) using custom electrodes and interface circuitry is integrated into a 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. The paper details the design, development, and initial testing of the prototype device.

II. System Overview

The device consists of a flexible cable-driven glove worn by the patient, a motion control system that resides in a backpack, sEMG electrodes in a sleeve worn by the patient, and a control interface. The following section outlines the key components of the hand rehabilitation system. The overall system concept in shown in Fig. 1.

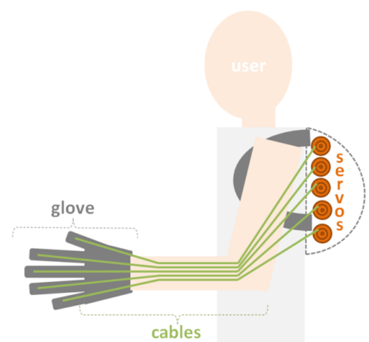

Figure 1: *The patient wears a glove that can apply tensile forces in order to aid finger extension and flexion. Servomotors and control electronics can be placed in a backpack worn by the patient while the glove is attached to actuated Bowden cables.*

A. Mechanical Subsystem

The glove itself is made out of a Spandex material, due to its flexible yet supportive form-fitting weave. Cable guides are 3D printed plastic pieces that hold the cables centered to each finger. 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 a single spool. Each spool was sized with two separate channels of different diameters 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 Modes

The glove has three primary control modes: a switch-controlled mode, a programmed position mode, and to use EMG signals. 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 with a scripted set of motions, or mimic motions from a sensorized glove on the unafflicted hand or that of a therapist; this functionality would be ideal for a therapist creating an exercise regimen for their patient. 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 active 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 and strength training. Active assistance aids the user in their intended movement, by supplying forces in the same direction.

C. Electromyography

Muscle movement in the body is controlled by signals sent down by the brain through the nerves. These signals generate electrical activity in the muscle (myoelectricity), which can be sensed by electrodes in what is called electromyography [14]. The surface EMG signal exists at a voltage range of 0-10 mV at a useable energy frequency of 0-500Hz [15]. These EMG signals can be acquired by a signal processor and sent to a control unit to operate electronic devices. Typically, the spikes in the power of the signal are used as the control cues. EMG controlled prosthetics have been in use for some time. Due to the naturally random nature of EMG waveforms, a simple control design is preferable for current devices [16].

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 for this system. The design includes two circular stainless steel contacts connected to an instrumentation amplifier circuit packaged within an epoxy shell. The amplification circuit consists of an instrumentation amplifier and differentially amplifies the signal by a gain of 20.

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.

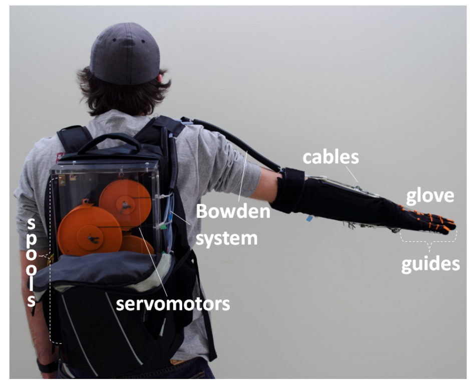

Figure 2: *The complete realized system design.*

A. Mechanical Subsystem

1) Overview: Mechanically, the design encompassed a subsystem which includes: a glove, cables, and actuators as shown in Fig. 2. 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 can wear if capable. 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. 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 as shown in Fig. 3. 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 material of the glove is a spandex, moisture-wicked material (Seirus Innovations, Thermax Deluxe Glove Liner).

Figure 3: *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.*

3) Cable Guides: The cable guide system was made od 3D printed parts, spread into three different types: fingertip, phalanx and palmar as shown in Fig. 4. 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 taut past the wrist, as seen in Fig. 3.

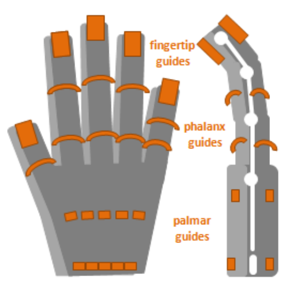

Figure 4: *Cable guide diagram with three types of guides: fingertip, phalanx, and palmar. Guides were placed in on either side of each joint in the finger in order to allow comfortable bending.*

4) Bowden Cables: In order to minimize the number of parts on the arm, and to allow more options in terms of actuation, a Bowden cable system was selected. 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 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, as shown in Fg. 5, 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. Details of the configuration for each spool are shown in Fig. **??**. The final rendition of the spools were 3D printed parts made of solid a single piece.

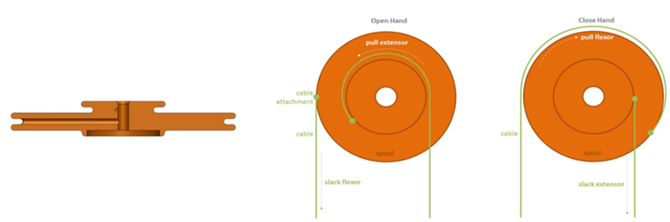

Figure 5: *Left: Two-Layered spool design cross-section. Top diameter for flexion, bottom diameter for extension of the fingers. Right: The top layer of the spools pulls the extensors for opening the hand. When extending the fingers, the extensor cables are slacked and vice-versa for the flexion of the fingers.*

The servomotors used (HiTec 5465 series) were able to rotate from 0° to 200° 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

Finger	Average Displacement Flexion (cm)	Spool Diameter Flexion (cm)	Average Displacement Extension (cm)	Spool Diameter Extension (cm)
Pinky	19.344	22.166	65.348	74.883
Ring	15.607	17.885	42.943	49.209
Middle	15.000	17.189	48.484	55.558
Index	16.756	19.201	55.667	63.789
Thumb	25.561	29.291	65.348	74.883

Figure 6: *Finger cable displacements and spool sizing.*

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 circuitry intergated into the control board. 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 Fig. 7 consists of signal processing, servomotor control (current limiting), and power. The signal conditioning portion of the board is powered by a battery pack that provides a 12V and a -12V rail that is isolated for patient safety. The servomotors and the MSP430 microcontroller are powered by a separate +6V battery pack to mimize noise introduced into the EMG signal processing. A small PCB for user inputs was also created.

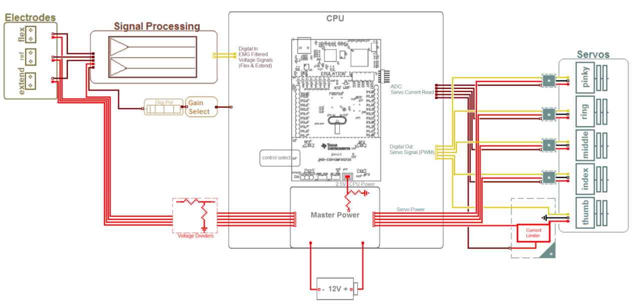

Figure 7: *System diagram with microcontroller in center. Electrodes connect to microcontroller through a signal conditioning circuit. Servomotors are current limited by the microcontroller. 12V power for system operation*

1) EMG Sensing: EMG was collected from the forearm, specifically the extensor digitorum communis and the flexor digitorum profundis, as detailed in Fig. 8. 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.

To keep out motion-based noise, a signal conditioning circuit was implemented. The signal conditioning design was based on the work of Edward Clancy [17]. Two second-order

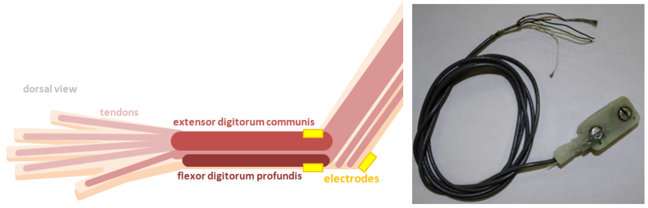

Figure 8: *Left: Major hand flexor and extensor muscles where myoelectric control electrodes were placed. Right: Custom EMG electrodes that were integrated into the sleeve.*

Butterworth filters were designed, a high-pass and a low-pass. Two separate gain stages as well as two filters were used per channel. 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 Fig. 9.

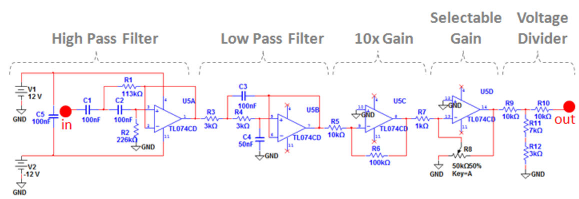

Figure 9: *Signal conditioning circuit diagram. The input is from the electrode-amplifiers and the output connects to the ADC on the microcontroller board.*

2) EMG Control: 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. Sampe acquired signals are shown in Fig. 10. A control program was written such that if the hand was closed and the extending EMG reached a

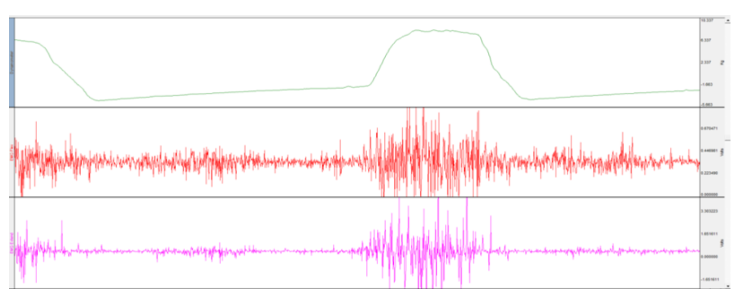

Figure 10: *EMG and force data acquired using the custom electrodes. (top) is force in pounds,(middle) is the EMG flexion signal in volts, and (bottom) is the EMG extension signal in volts*

certain threshold, the servomotors would open the hand. And 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 and Discussion

Overall, the system demonstrates a functional prototype of the design: a portable solution to hand rehabilitation. The complete system can be seen in Fig. 2. The following describes evaluation of the system.

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 Fig. 11. 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.

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.*

B. Safety

Since this system is to 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. As the design of the system progressed, 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 electical shock. However, the system bypasses this concern by using battery packs, and is thus fully electrically isolated from earth ground.

C. Electromyogram Control Calibration

Electrodes were utilized as a means to control the glove with the users own EMG signal. This was implemented by placing two electrodes on the forearm, of the hand that was being actuated. 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 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.

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. The future of this device will continue to aim for a universal design that persons recovering from stroke, or people with other needs, may use for rehabilitation or assistance.

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