Electrical and Biomedical 4BI6
Final Report

Design of a Hand and Wrist Exoskeleton Motion Assistance in Daily Activities

by

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ABSTRACT

This report covers the design of an exoskeleton glove worn by the user to reinforce grip strength. It does this by locking the joint positions of the user in position such that the user cannot let go unless the exoskeleton receives a release signal by the user. This has applications for individuals who may be physically weaker such as the elderly or those with neuromuscular diseases. Signal acquisition is made through force and flex sensors and controlled through the arduino nano. Prototyping of the physical exoskeleton was made through meccano pieces. The main power requirements of the glove are that the exoskeleton must have a holding force of 5 lbs without exerting excess force on fingers of the user. By designing a cable loop lock mechanism with the use of solenoids, the exoskeleton is able to add holding force and provide at least 15 lbs of maximum holding force. This is in contrast a huge improvement over the cable tension system. The exoskeleton structure was designed to be compact enough to fit all actuators, locking mechanism, and the physical exoskeleton structure on to one glove.

Keywords: power assist exoskeleton

ACKNOWLEDGEMENTS

Thanks to my partner, Michelle Ngai, for all the stimulating discussions, sparks of random ideas, and continuous support throughout the year. Thanks to Dr.Doyle, my project supervisor, for all the helpful advice and the continuous support of the project over the year and keeping the project on track.

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Introduction

1.1 Background and Literature Review

The term exoskeleton refers to an external wearable robot that is worn by the user to extend human muscle strength. It is designed in a skeletal manner in the sense that the joints of the exoskeleton line up correspondingly with the joints of the human limb on which it is worn. The force exerted by the exoskeleton is thus exerted on to the joints of the human to create power-augmented motion.

In recent years, there has been an increasing interest in the development of different kinds of exoskeletons. This is made possible now by many technological advancements: some including reduction in sizes of actuators such that exoskeletons can by worn by a human user, improvements in reduction of size of power supplies and lifetime, better control techniques, etc.

The main development areas include exoskeletons for usage in the military such as the Berkeley Lower Extremity Exoskeleton for power augmentation (BLEEX)[5], for industrial workers such as the knee assistive exoskeleton [6] to use for carrying heavy loads, and exoskeletons for rehabilitation purposes [4] where the exoskeleton guides the limb through accurately mimicking certain limb motions. Although all of the above exoskeletons extend human muscle strength in some way, the applications of the exoskeleton is geared towards specific professions (military, industrial workers) and special purposes (rehabilitation) making them not very useable for the average person. For example, in the case of military and industrial workers, the exoskeletons are usually made for the lower extremity or even full body exoskeletons that allow the user to perform "super human" abilities that would not be used and worn by a normal person daily. In the rehabilitation case, the exoskeletons are attached to a permanent fixture, which again would not be very practical for the normal person. To support this, there is increasing evidence for the need of assistive robotic devices for people on a day-to-day basis in the future. As of today, almost 20% of the population is over 65 and by 2050, this figure should reach 35%.[2] This means that there will be an increasing number of people who may be physically weaker such as the elderly and would benefit from an assistive exoskeleton device to aid them in daily tasks such as grasping heavy bags, housework such as cooking and manipulating pots and pans, pouring water from a pitcher, etc. These assistive exoskeleton devices would allow for those who are physically weaker such as the elderly and those who have neuromuscular diseases to maintain their lifestyle and continue to be able to fulfill daily tasks.

For daily tasks, many motions involve the arm. Motions involving grasping and the wrist (such as pronation and supination of the wrist) are weakest in comparison to other motions such as lifting by stronger forearm and bicep muscles. Therefore, the goal of the overall project is to design an exoskeleton for the hand/wrist to assist in those weaker motions including reinforcement of grip strength for grasping and rotation of the wrist for daily tasks. This report will focus on the design of an exoskeleton worn as a glove to reinforce grip strength in locking the grip in position. (See my partner's report: Michelle Ngai for the design of the exoskeleton for rotation of the wrist)

Anatomy of the Finger Joint

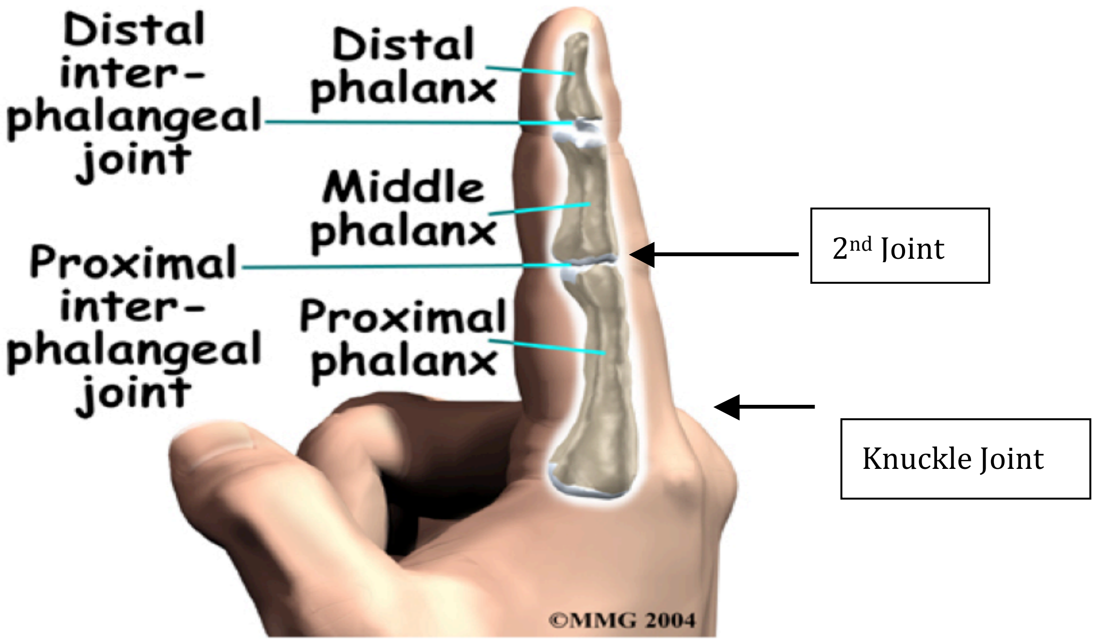

Figure 1 - Anatomical Diagram of Finger Joint
[1]

Power grasps mainly involve the last 3 fingers of the hand. The 2nd index finger and the thumb are used more for finesse motions and the thumb plays a large role in stabilization and not so much in exerting a holding force. As a result, only the last 3 fingers of the hand are actuated. To lock a grip in a certain position, the 2nd joint and the knuckle joint of the last 3 fingers must be locked. Thus, the design of the exoskeleton will focus on actuating the last 3 fingers of the hand and locking the knuckle joint and 2nd joint of the last 3 fingers.

1.2 Objectives and Scope of Project

Main Objective:

To design a wearable, safe, and useable exoskeleton that is activated and controlled by the user's motions to reinforce the grip strength of the user in power motions of grasping

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[1] http://www.health-res.com/metacarpophalangeal-joint-swelling/

for daily tasks. The exoskeleton should be able to hold the user's grip in position at a minimum of 5 lbs of holding force per joint.

Objectives of Improvement from Literature Review:

- To detect user force and motion information for the purpose of control through force and flex sensors as opposed to EMG detection as implemented in many designs in current research literature.
- To differentiate actual grasping forces from regular contact forces on the hand. In previous implementations [1], one of the areas needing further work is the ability of the exoskeleton to accurately differentiate measured force signals of grasping from force signals measured from the environment (such as the hand brushing against an object). In other words, improvements must be made to ensure that the exoskeleton is not accidentally actuated by external contact forces.
- To make this exoskeleton a portable assistive device that can be worn as a glove. In regards to exoskeletons for the wrist/hand, most implementations observed were for rehabilitation purposes. [4] These are by nature extremely bulky and not portable.
- Previous portable/wearable exoskeleton implementations observed [3,7] only focus on implementing one type of motion (i.e either grasping or wrist motions). This project will have the integration of two motions (reinforcement of grasping and rotation of wrist) on one exoskeleton. (For the design of rotation of the wrist, refer to Michelle Ngai's report).
- To design an exoskeleton glove that can hold the grip position with holding forces of 5 lbs or more per joint. From literature reviews, current designs have implementations of grasping forces of up 8 to 10 N (1.8 to 2.2 lbs) per joint. [9]

Safety Objectives:

- To not exert excessive forces on the fingers of the user (< 2 lbs of force per finger) but at the same, the exoskeleton must have a holding force of > 5 lbs
- To implement tactile/visual/audio feedback to the user to warn the user the actuation of the exoskeleton
- To implement a "kill" switch to override the actuation decision of the exoskeleton

Assumptions:

The user must have a functional hand that can complete the motions of grasping to activate sensors in exoskeleton. The exoskeleton will be worn on the non-dominant hand. This is due to the possibility that the exoskeleton may interfere with the ability to complete finesse motions (mostly done by dominant hand) as it is focused on power motions. Also, it is assumed the exoskeleton will be used for daily tasks and not for tasks that require extreme force.

General Approach to the Problem

The design of the exoskeleton is broken down into 3 main subsections as shown in Fig.1.

Figure 2 - Flow chart of general design components of exoskeleton

The input data (force and motion data of the user) is detected through force and flex sensors on the hand. Both the force and flex sensors are variable resistors. The force and flex signals from the sensors are converted into a voltage through analog signal conditioning, which consists of a voltage divider network.

The voltage divider network is interfaced to the microprocessor on which the control software determines if the user is implementing a power grasp and also when to release when the exoskeleton is grasping. This is done by setting threshold values in the control algorithm for both force signals and flex signals. In other words, to initiate grasping the fingers of the hand must be grasping above a specified threshold force and the fingers must be flexed beyond a certain angle in order to actuate the exoskeleton. If both threshold values are met, an output signal is sent from the microprocessor to the actuators on the exoskeleton. By setting the condition of having a certain amount of force on the fingers and for the fingers to be flexed beyond a certain angle, this ensures that the exoskeleton only actuates for a power grasp and not from normal contact forces (such as placing the hand palm down on a flat surface).

In this design, pull solenoids are used to actuate the exoskeleton and lock the joint positions in place. The locking method is done through a cable loop system designed specifically for this application, which increases the holding force and locks two links together relative to each other. Further details are explained in the methodology of solution section. The physical structure of the exoskeleton is designed from meccano pieces. The physical exoskeleton structure is designed to wrap around the fingers of the hand and not to lie on top of the fingers to reduce the size of the exoskeleton on the glove and increase portability and wearability. Power grasps mainly involve the last 3 fingers of the hand and thus, only the last 3 fingers of the hand are actuated: specifically the knuckle and 2^{nd} joint of each finger.

The release mechanism for the exoskeleton is implemented by the flex sensor placed on the 2^{nd} finger. Since the 2^{nd} finger is not actuated and is free to move while the exoskeleton implements a power grasp, the release mechanism is implemented such that the exoskeleton will release the grasp if the 2^{nd} finger is no longer flexed.

Chapter 2

STATEMENT OF PROBLEM AND METHODOLOGY OF SOLUTION

This section will cover the theory of operation behind the major components of the exoskeleton. This includes the sensors used in data acquisition as well as the actuation method (cable loop system), actuators, and physical structure of the exoskeleton. The development of the solution is discussed as well as to why the design of those components were chosen over others.

2.1 Data Acquisition (Sensors) and Analog Signal Conditioning

Problem

Reliable force and flex sensors were needed to detect control signals from the user to signify a power grasp from the user. They also should be flexible and small enough in size as they are to be placed on the fingers and hand and should not be obtrusive to the user.

Solution

For force sensors, the initial solution was to use QTC (Quantum Tunneling Composite) pills as shown in Fig. 3 below.

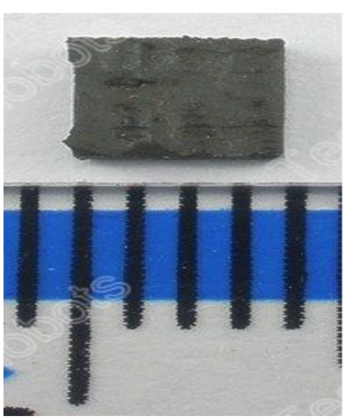

Figure 3 - QTC Pills

QTC pills are extremely small with 3.6 mm x 3.6 mm and is a flexible polymer which changes its resistance when force is applied on to them. The higher the force on the QTC pill, the lower the resistance. This at first matched all design criteria, however, it was not chosen in the end due to its inconsistency of matching a force to a related resistance. No reliable measurements could be taken for the QTC pills The QTC pills were tested using the same apparatus that is used to test FSR sensors (later described) shown in fig. 4. As a result of its inconsistent resistance readings, QTC pills were not used

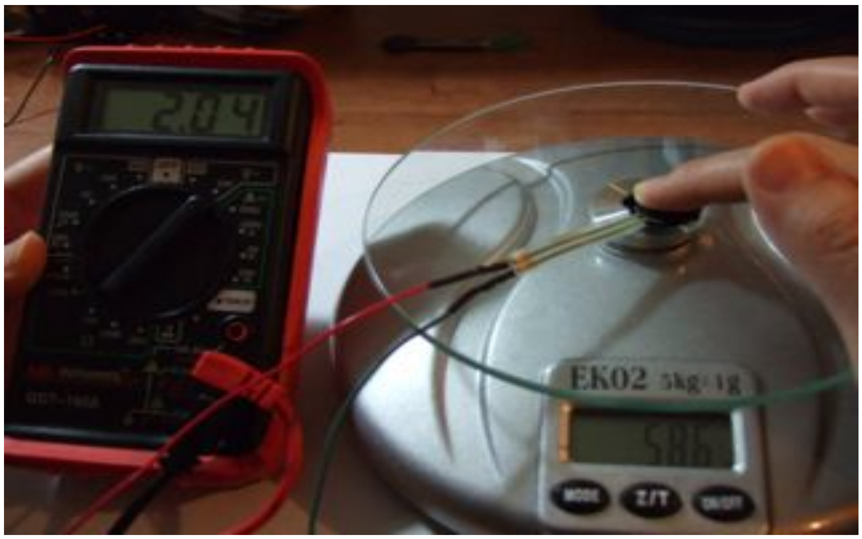

Figure 4 - Testing Apparatus for Force Sensors

The force sensors that were used in the end were Interlink FSR's (Force Sensing Resistor) as shown in Fig. 5.

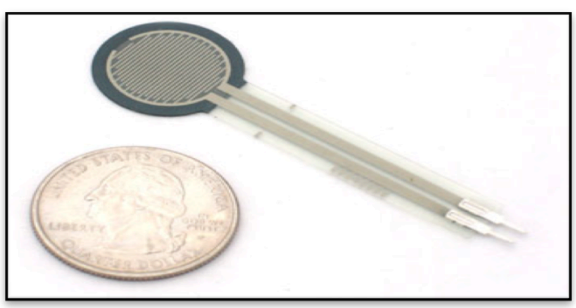

Figure 5 - Interlink FSR

These worked very similarly to QTC pills. They were flexible, small, thin sensors. The higher the force applied to the sensor, the lower the resistance. These resistors were tested using the apparatus shown in fig. 4. A force was applied to the sensor on top of a scale and the force sensor was also connected to a multimeter. Both force (g) and resistance values were read at the same time. Table 1 shows the corresponding force and resistance values of the force sensor.

Table 1 - Corresponding Force and Resistance Values Measured from Interlink FSR (fsr values from 200 to 2 kg)

Force (g)	Resistance (kΩ)
200 (0.44 lbs)	6.0
400 (0.88 lbs)	3.2
600 (1.32 lbs)	2.1
800 (1.76 lbs)	1.7
1000 (2.2 lbs)	1.4
1200 (2.64 lbs)	1.12
1400 (3.08 lbs)	0.91
1600 (3.52 lbs)	0.82
1800 (3.96 lbs)	0.78
2000 (4.4 lbs)	0.73

*the equivalent force in lbs is shown on the right in brackets ()

Two other trials were completed which are shown in the appendices.

Flex sensors were used as well a shown in Fig. 6.

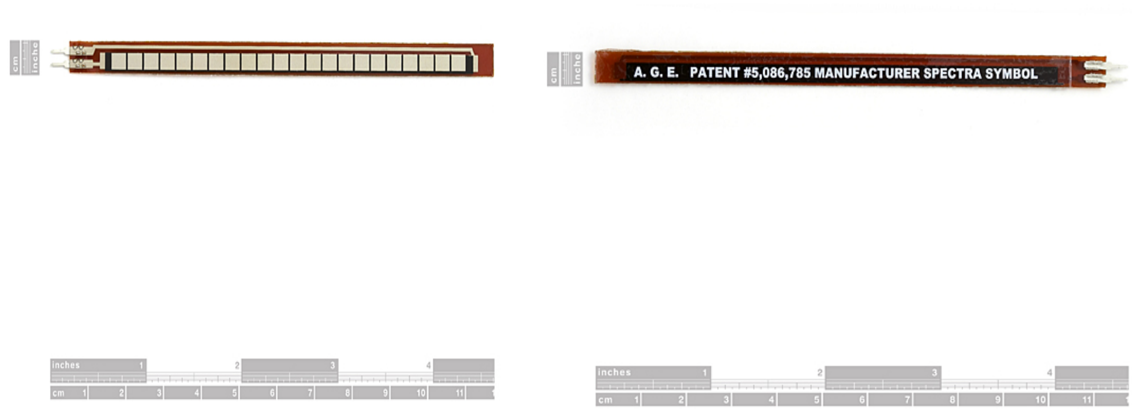

Figure 6 - Flex sensor. Front (left). Back (right)

The flex sensors worked in a similar manner to the FSR. They are variable resistors with resistance value varying with the bend angle. These flex sensors were unidirectional with the gridded side as shown in Fig. 6 as the top, and the black side to be the underside (the bottom). Assuming 0 degrees of bend angle as the flat position and bending downwards as positive, as the bend angle increases, the resistance increased. Resistance values at several bend angles were measured. A table of corresponding values of bend angle and resistance is shown in Table 2.

Table 2 - Bend Angles and Corresponding Resistance Values for Flex Sensor

Bend Angle (degrees)	Resistance (kΩ)
0 (rest)	10
50 (large grip)	17
90 (medium grip)	20
125 (small grip)	30

To interface the sensors with the microcontroller, the sensors are placed in a voltage divider network to convert the force and flex signals into a voltage signal and the output of the voltage divider is output to the ADC of the microcontroller. The voltage divider network is also in series with a buffer to isolate the voltage divider form the input resistance of the microcontroller. The voltage divider network with the sensor is shown in figure 7.

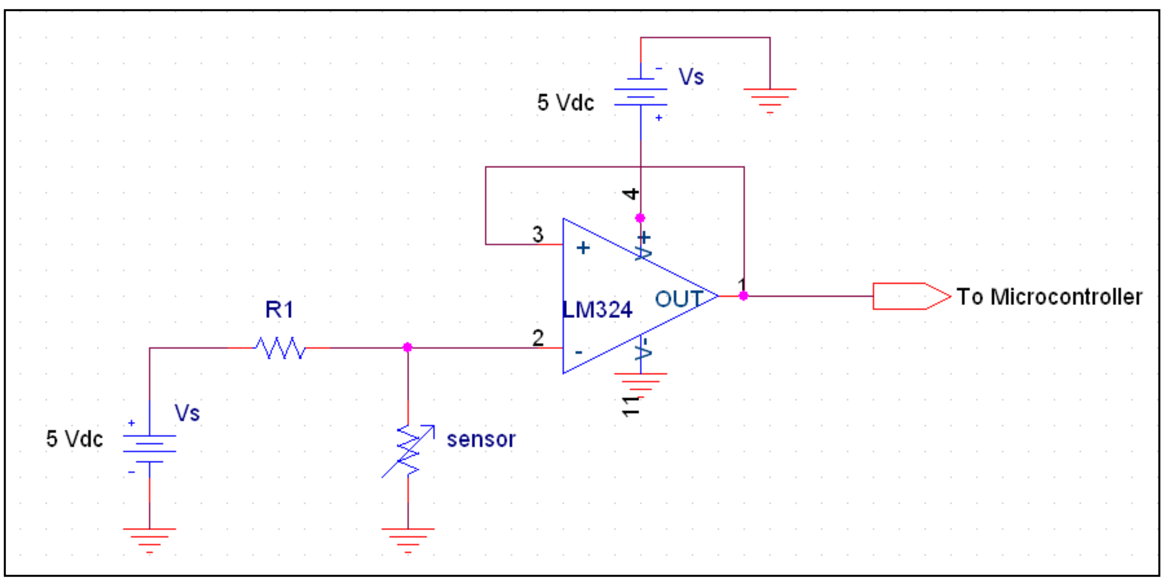

Figure 7 - Voltage Divider Network To Convert Sensor SIgnals to Voltage Signals

The voltage to the microcontroller is calculated as

$$Vo = \frac{Rsensor}{R1 + Rsensor} x5 \text{ (eqn 1).}$$

The 5 V source is chosen since the ADC of the microcontroller (Arduino Nano) has a voltage swing of 5 V. R1 is selected based on the resistance range of the sensor and the desired threshold resistance values to maximize usage of the full 5 V input range of the ADC. With R1 selected, the threshold voltage values can be determined from eqn.1 and used in the control algorithm to determine if a power grasp is implemented or if the release signal is input (2nd finger is no longer flexed). As an example, for FSRs the resistance varies from 0 to approximately 6 kΩ. The desired force for indication of a power grasp is selected at 800 g (1.76 lbs) for the specific individual which corresponds to Rsensor = 1.7 kΩ and R1 is selected to be 2 kΩ. Thus, the threshold voltage value is 2.29 V as calculated from eqn. 1. Since the resistance decreases with greater force, then the input voltage to the microcontroller must be < 2.29 V in order for the force to be considered high enough to be a power grasp.

Sensor Placement

A power grasp must be accurately detected by the exoskeleton. This means that the placement of the sensors plays an important role. The areas of pressure over the hand while power grasping was observed. For power grasping, the 3rd and 4th fingers exert the most force. Regardless of the shape of the object, the pressure while grasping occurs at the tip of the fingertips for those two fingers. Thus, two force sensors were placed at the fingertips of the 3rd and 4th fingers. Although the 5th finger also plays a large role in power grasping, it has functions similar to the thumb in that it also plays a large role in stabilization. Thus, the location of pressure during a power grasp for the 5th finger depended greatly on the shape of the object. For certain objects, the 5th finger does not exert much force and for other shapes, the 5th finger exerts more force. Due to the nature of power grasping with the 5th finger and inconsistent pressure applications along the finger, the 5th finger was not a reliable source to provide power grasping information. As a result, no sensors were placed on the 5th finger. The flex sensor was placed on the 2nd

finger. Reasoning includes since the flex sensor is the signal for release (the finger with the flex sensor must be in an unflexed position while the other fingers are flexed), the finger on which it is located on must be able to easily be in an unflexed position while the other fingers are still bent. The motion of the 3rd and 4th fingers are hard to separate independently but the 2nd finger is very independent of the other fingers. In addition, the 2nd finger plays a larger role in finesse grasping motions as opposed to power grasping and like the 5th finger, the pressure readings from the 2nd finger varies depending on the size and shape of the object. Therefore, the 2nd finger was not a good choice for the placement of force sensors but was excellent for the placement of the flex sensor, which was located along the 2nd finger on the palm side.

2.2 Actuators, Actuation Method, Physical Structure

The solution to this part proved to be the most challenging component of the project. The goal at first sounds simple: the links of the exoskeleton are moved into a grasping position by the hand. A signal is received indicating that a power grasp is implemented and the exoskeleton locks the links of the exoskeleton in place. All of the components involved must fit on to a glove.

Problem:

The selected actuator for the exoskeleton glove must be small and light enough to be able to fit on a glove and be able to produce a holding force of at least 5 lbs. This presents a problem itself in that the larger the holding force required, the larger the actuator. The exoskeleton must also have a locking mechanism that efficiently locks the joints of the exoskeleton with respect to each other given the limited amount of holding force provided by smaller actuators. Thus, the locking mechanism should actually increase the amount of holding force in addition to that of the actuator. In addition to this, the physical structure of the exoskeleton must not exert more than 2 lbs of force on the fingers of the human user wearing the exoskeleton glove. The physical structure of the exoskeleton worn on the hand as a glove should also be comfortable for the user and be able to follow the movements of the fingers without causing discomfort. This problem and the corresponding methodology of solution is thus broken down into 3 major parts describing the actuators used, actuation method (or locking mechanism), and the physical structure of the exoskeleton.

Actuators

The purpose of the actuators in the exoskeleton is to engage the locking mechanism (ie. Pulling cable, pushing components together, etc) and lock one link with respect to the other. The selection of an actuator for this application should ideally have a very high holding torque to keep the locking mechanism engaged.

Feasible and low cost actuators that were considered included dc motors, stepper motors, and pull solenoids. DC motors were advantageous for their availability in many different sizes especially smaller sizes. However, for the size required, they did not exhibit a high enough stall torque ("holding" torque). Other options were looked into including adding gearing to the shaft of the motor to increase holding torque as well as position control to lock the positions into place. However, position control would involve adding position encoders to the shaft of the motor as well. Both gearing and adding position control would add to the bulkiness of the exoskeleton as well as adding to the complexity of the structure, which in turn would decrease the robustness of the exoskeleton to physical contact. As a result, the option of using DC motors was deemed not feasible and the goal became to focus on the mechanical implementation of the locking mechanism such as relying on the holding torque of the motors and external mechanical devices that would increase the holding torque which will be discussed in the section of actuation method (locking mechanism).

Stepper motors and pull solenoids both provide a higher holding torque or force compared to DC motors. Stepper motors are similar to dc motors where motion is created through rotation of a shaft. Stepper motors provide a constant holding torque regardless of the position of the shaft or the number of rotations of the shaft. This is not the case for pull solenoids.

Solenoids consist of a coil, a plunger in the coil, and a tubular casing that surrounds the coil. Pull solenoids work by running current through a coil housed in a casing (such as a tube) creating an electromagnet. A plunger located within the coil is then pulled inwards due to the electromagnetic field. For pull solenoids, the holding force depends on the stroke length of the solenoid. The stroke length is the distance between the end of the plunger (the cone) and the end of the solenoid tube (the plug). Refer to figure 8 for the diagram of a solenoid. The holding force of a pull solenoid is inversely proportional to the stroke length and thus, the more the plunger is pulled in for a pull solenoid, the higher the holding force. For small stroke lengths, the holding force provided by a pull solenoid is very high and much higher than the force that can be provided by a stepper motor of similar size.

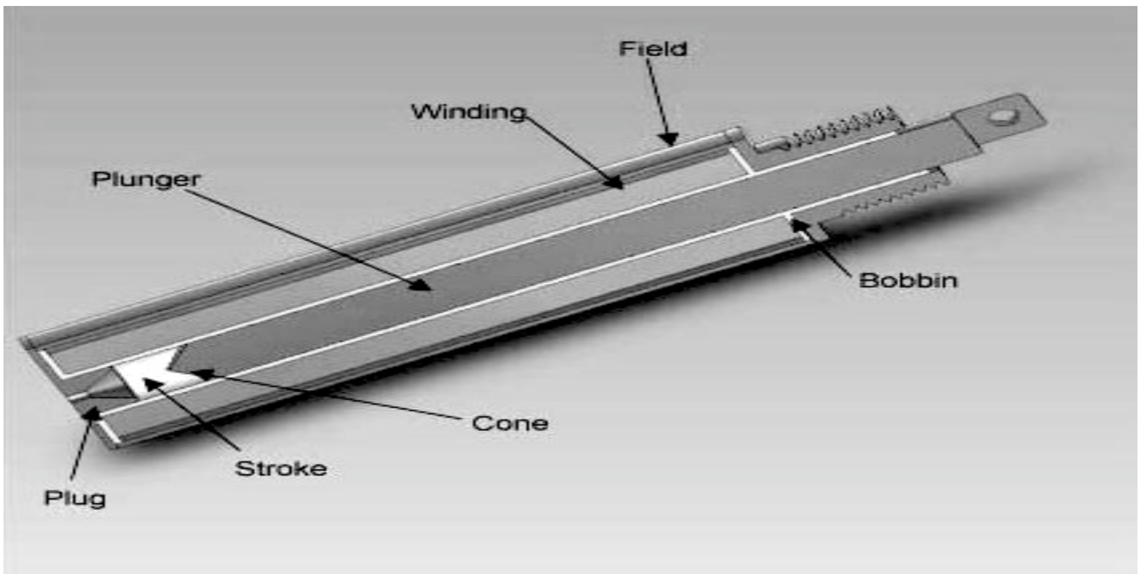

Figure 8 – Diagram of Cross Section of a Pull Solenoid[2]

For the design of this exoskeleton, solenoids were chosen to be used as the actuators. This was the best choice due to the fact that the method to engage the locking mechanism was designed to only required a very short actuation distance thus taking advantage of the high holding force of pull solenoids at small stroke lengths.

The specific solenoid chosen is Pontiac Coil Model L-75 F0472A which is a 12 V intermittent solenoid. Intermittent solenoids are not designed to be on for long continuous periods of time as the coil of the solenoid will heat up and may melt the coil. A safe range of operation is 1 minute on and 2-3 minutes off. Although a continuous solenoid is ideal (can run for an indefinite amount of time), at the amount of holding force required (5 lbs),

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http://www.guardian-electric.com/images/BasicOperationofSolenoids.jpg continuous solenoids are much larger than intermittent solenoids and not practical for this application as they are too large to fit on to a glove. This is due to the fact that less current runs through a continuous solenoid to prevent heating of the coil and thus, a larger coil is required to compensate for the lower current to provide the same amount of holding force. Although the tradeoff between size and holding force and the length of activation time for solenoids exists between intermittent and continuous, intermittent solenoids were chosen as the shorter activation time length is sufficient for time required in power grasping for daily tasks. In return, intermittent solenoids provide a high enough holding force at a small size which is perfect for the application of this exoskeleton. For the L-75 solenoid chosen, a chart showing the stroke length and the corresponding holding forces is shown in table 3 below. For the full data sheet of the solenoid, refer to the appendices.

Table 1 - Stroke Length and Corresponding Holding Forces for L-75 Pull Solenoid

Stroke Length (cm)	Holding Force (kg)
0	2.38 (5.25 lbs)
0.16	1.81 (4.00 lbs)
0.32	1.30 (2.87 lbs)
0.64	0.79 (1.75 lbs)
0.96	0.57 (1.24 lbs)
1.27	0.40 (0.87 lbs)
1.58	0.31 (0.69 lbs)
1.91	0.17 (0.37 lbs)

*Holding force in lbs is shown on the right of the holding force in kg in ()

From table 3, it can be seen that the L-75 intermittent solenoid has a holding force of 5 lbs (satisfied minimum requirements) at 0 cm stroke length. Beyond a stroke length of 0.64 cm, the holding force becomes very weak. Thus, the locking mechanism must be engaged within 0.64 cm. This will be described in the next section.

Actuation Method (Locking Mechanism)

The basic component of the exoskeleton consists of the link-joint-link structure that lie adjacent to the fingers of the hand with the hinge of the joint structure lined up with the corresponding joint on the human hand. The ends of each link are attached to the finger (on to the glove). Refer to figure 9 for a diagram of the link-joint-link structure that exists throughout the exoskeleton for the finger joints of the last three fingers as well as the knuckle joint.

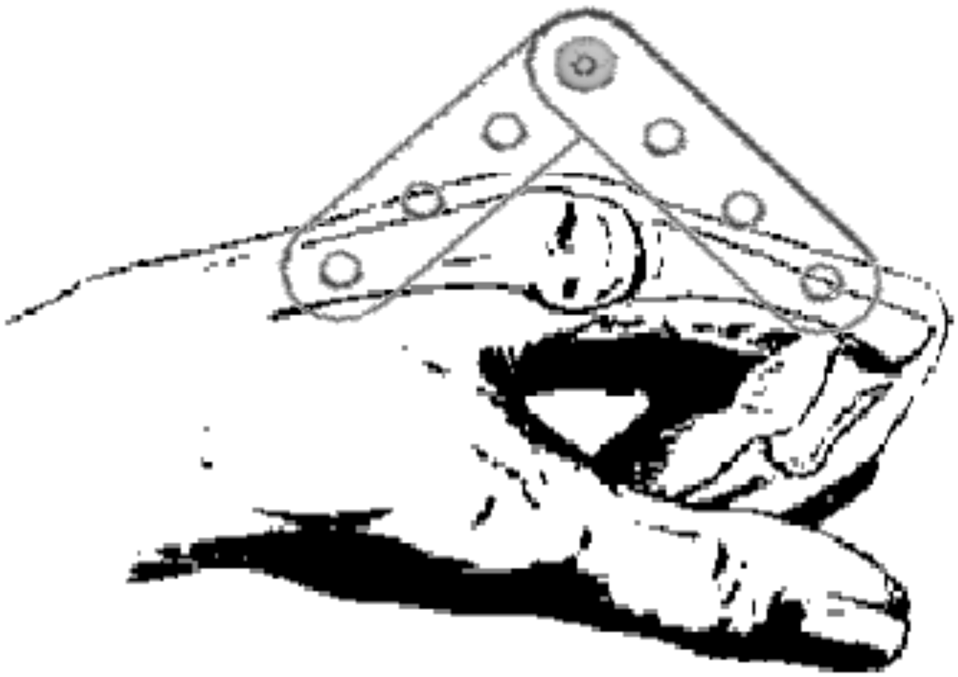


Figure 9 - Diagram of Exoskeleton Link on Joint

The purpose of the link-joint-link structure is that it will follow the movement of the finger joint in a power grasp and when the exoskeleton receives a signal that a power grasp is implemented, the links will lock position. Since the links are adjacent to the joint and are attached to finger, the human joint is thus locked into position as well. To hold a grasp, the 2nd joint and the knuckle joint of the last three fingers must be locked. Thus, this basic structure is seen throughout the exoskeleton on the 2nd joint and knuckle joint of the last three fingers.

In other research literature, a common method of actuation is the cable tendon drive system. Yasuhisa and his colleagues [9] used such a system in their exoskeleton where a cable is attached to each link of the exoskeleton finger structure. For a finger consisting of three links and two joints, his research team used three cable tendons for each link. Each cable tendon is pulled by three DC motors independently. The length of the cable tendons are adjusted according to a PD controller. Their cable tendon drive mechanism is shown in figure 10.

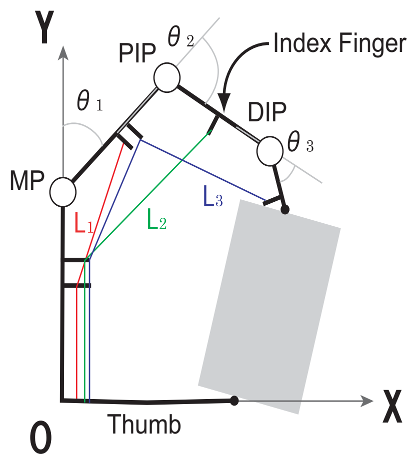


Figure 10 - Cable Tendon Drive Mechanism by Yasuhisa and Colleagues [9]

The initial solution to designing a locking mechanism for the exoskeleton glove was to try and use the cable tendon drive mechanism shown in figure 10 but have the cables pulled by solenoids. The length of the cable to each finger was to be a set length from the plunger of the solenoid. As the solenoid was pulled inwards (stroke length decreases), it would pull the link inwards as well. Each grasp position would correspond to a specific stroke length distance. In order to make use of the high holding force of the pull solenoid, the actuation distances to cover all ranges of joint positions had to be as small as possible. Thus, the cable had to be attached as close as possible to the joint of the link. There was a major drawback in this method as it produced an effective holding force of less than the maximum holding force of the pull solenoid itself. This was simply due to the fact that the torque exerted by the cable on to the link is les than the torque exerted by the finger pressing back on to the link due to the longer length of the finger from the joint compared to the short length of between the joint and the cable attachment site (since torque = rfsin(theta), if r decreases, the torque decreases as well). Refer to figure 11 (the red arrow is the length from the joint to the cable attachment site and the green arrow is the length from the joint to the finger). Since the pull solenoids selected for the exoskeleton was only able to exert a maximum holding force of 5 lbs at the 0 cm stroke length, this approach would have holding forces of less than 5 lbs. Although this mechanism would be simple to implement, it did not meet the minimum requirements.

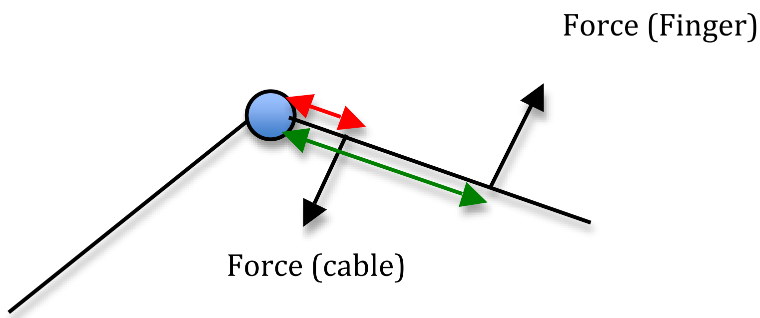


Figure 11 – Explanation of lower torque exerted by cable compared to torque exerted by finger

Another locking mechanism had to be designed. As explained previously, a distinct disadvantage occurs with using pull solenoids in that it only has a high holding force over a short stroke length (less than 0.64 cm). As a result, the cable attachment site must be as close to the joint as possible resulting in less effective holding torque (length of joint to finger is longer compared to length of joint to cable attachment site). This problem indicates the need for a locking mechanism that is actually able to increase the holding force of the motor such as relying on friction forces at the joint by an external mechanism. Since this external device could only be activated when the exoskeleton was on and should not add extra bulk to the glove, a lock mechanism that used cables like the previous solution was designed.

A new design solution was developed for the lock mechanism: the cable loop lock mechanism as shown below in figure 12.

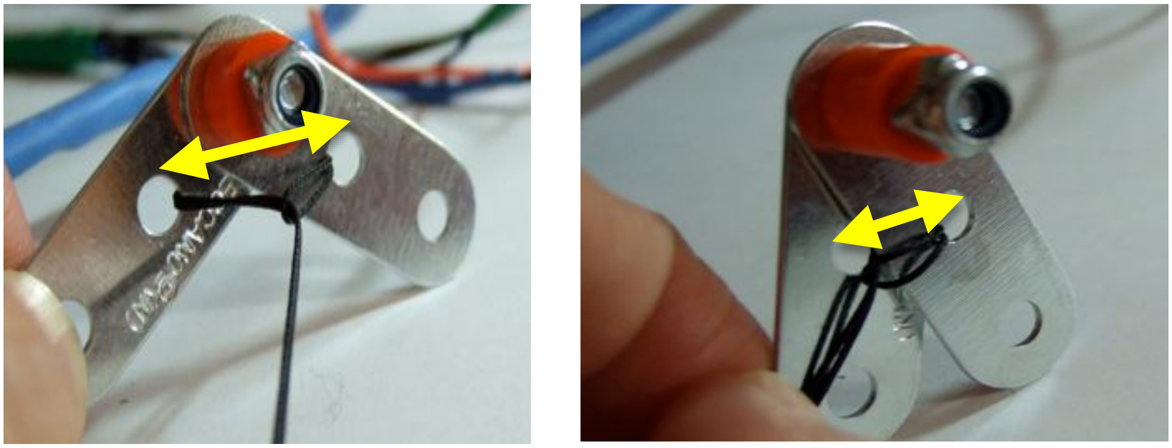


Figure 12 - Cable Loop Lock Mechanism. (Left) Larger loop, larger joint angle. (Right) Cable pulled in, smaller loop, smaller joint angle. The arrows indicate the distance between the two links, each corresponding to a specific joint angle

The same link-joint-link structure attached to the human finger is used in this design as well as shown in figure 9. However, instead of having a cable attached simply to one point on the link, the cable loop lock mechanism relies on a very simple technique, which is to form an adjustable loop around the joint passing through the two links. By pulling on the cable, the loop tightens and the joint angle between the two links decreases. The further the cable is pulled, the smaller the joint angle. The cable is pulled by the pull solenoids located on the back of the hand on the glove. Thus, as the stroke length decreases (solenoid plunger is pulling the cable more and more), the joint angle between the two links decreases. At stroke length of 0 cm, the joint angle is at it's smallest and the grip at this point is at its tightest. Refer to figure 12 for an illustration of this. If the solenoid can hold this position, the joints of the finger are now locked in to position. If the solenoid is not activated, the loop is free to slide and adjust the to joint angle formed by the user. By using this technique, the links are always moving relative to each other and locked in position relative to each other.

The next thing to investigate through the cable loop lock mechanism is if it can sufficiently provide a high enough effective holding force. In order for this to be accomplished, the mechanism must be able to add to the holding force of the solenoid itself as the use of solenoids innately causes the effective holding force to be less than the maximum rated holding force of the solenoid itself.

Firstly, in order to be able to take advantage of the high holding force of solenoids, the stroke length distance of the solenoid required to cover all possible joint angle ranges must be small. In the case of the cable loop mechanism, the total stroke length distance required to cover all possible joint angle ranges is determined by the length between the two links through which the cable passes. This length is shown in figure 12 by the arrows. To determine a value, the length between the two links is measured at minimum joint angle (maximum bend of fingers – tight grip) as well as at maximum joint angle (minimum bend of fingers – no grip). The difference between the two lengths measured at minimum and maximum bend determines the stroke length distance of the solenoid required to cover all possible joint angle ranges. A table of values is shown below (table 4) for the 2nd joint of the last three fingers and the knuckle joint. The values shown below are the final values measured from the prototype exoskeleton built.

Table 3 - Distance between Links at Maximum and Minimum Joint Angles

Finger Joint	Length at Maximum Bend (cm)	Length at Minimum Bend (cm)	Stroke Length Distance Required (length at max bend – length at min bend) (cm)
2nd Joint of 3rd finger	2.1	1.6	0.5
2nd Joint of 4th finger	2.1	1.6	0.5
2nd Joint of 5th finger	1.5	1.0	0.5
Knuckle Joint (Right)	1.6	0.8	0.8
Knuckle Joint (Left)	1.6	0.8	0.8

From table 4, it is evident that the 2nd joint of the last three fingers requires a stroke length distance of 0.5 cm whereas the knuckle joint requires a stroke length distance of 0.8 cm to cover all possible joint ranges. These values are measured to encompass the joint angles from a completely no grip situation to a very tight grip. Hence, the stroke length distance actually required to cover the full range of joint angles for a power grasp is less than that seen in table 4 and should fall within the range of 0 to 0.6 cm as the pull solenoid can only provide a sufficient amount of holding force within 0.6 cm of stroke length. Therefore, the cable loop lock mechanism satisfies the first criteria in that that stroke length distance required to actuate the lock mechanism for all joint angles is less than 0.6 cm and can fully take advantage of the higher holding force of pull solenoids at a small size.

As seen in table 4, the 2^{nd} joints of the last three fingers are require the same stroke length of 0.5 cm to cover all joint angles. Similarly, the knuckle joints require the same stroke length of 0.8 cm as well. Thus, to save costs, only two solenoids can be used: one to actuate the 2^{nd} joints of all the last three fingers and another to actuate the knuckle joints. If only two solenoids are to be used, the attachment of the cable from the links to the plunger on the solenoid is very important. In order to ensure that the solenoid pulls equal distances for all finger joints, the direction of pull on the cables for each joint must be in the same direction since the direction from the solenoid to each finger will be different. This is done by combining all of the cables from each finger joint at one intersection point where the cables then become one thick stream of cables. The solenoid then pulls on the end of the cables grouped together. This will cause an equal vertical displacement in all three cables. This idea is illustrated in figure 13.

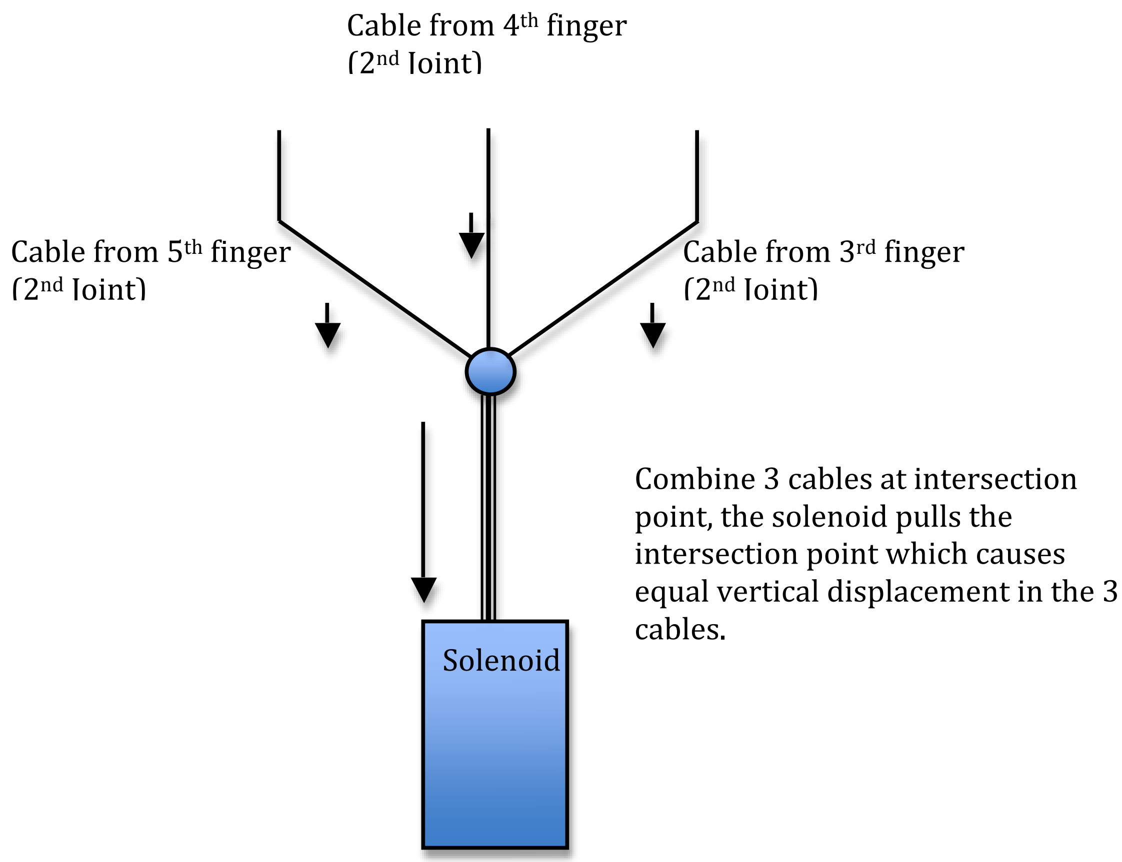


Figure 13 – Connections of Cables to Solenoid to Ensure Equal Vertical Displacement as Solenoid Pulls (showing cable connection for last 3 fingers 2nd joint) for the case of using 2 solenoids

Also, to ensure that the full range of joint angles is covered by the stroke length of the solenoid, it must be ensured that the lengths of the cable are made such that when the joint angle of the links are at the smallest angle possible (tight grip), the plunger of the solenoid reaches a stroke length of 0 cm when the cable is fully outstretched. Also, by doing so, the set cable length ensures that the exoskeleton does not place too much pressure on to the fingers of the user. This is due to the fact that the maximum pull of the solenoid will correspond to the smallest joint angle position and cannot go beyond that and thus cannot exert further pressure on to the fingers.

The 2nd investigation to the design is the amount of holding force the cable loop mechanism can withstand. It was found through testing which is later described in this report, that the cable loop mechanism is able to produce a holding force that is 6-7 times greater than that provided by the cable tendon drive mechanism. At a maximum hold force, the cable loop lock mechanism per joint can withstand at least 15 lbs of force. This is at a tight grip where the stroke length of the solenoid is at 0 cm. At the largest grip such that the stroke length is at 0.3 cm, the cable loop lock mechanism can hold up to 8 lbs per joint.

Physical Structure

The physical structure of the exoskeleton consists of the basic component link-joint-link structure on a glove as shown in figure 9 throughout the exoskeleton on the 2nd joint of the last 3 fingers as well the knuckle joint. The main goal of the physical structure is to be as unobtrusive and compact as possible and must not limit the joint motion of the user. It should also not cause any discomfort. The physical structure was built through meccano pieces, which provided a large selection of small metal parts that could fit on to a glove. Refer to figure 14 for a CAD drawing of the physical structure of the exoskeleton for the 3rd finger. This structure is sewn on to the glove.

To ensure compactness, the exoskeleton structure was built around each finger with the link-joint-link structures adjacent to each finger as opposed to lying on top of the finger. To attach each of the adjacent link-joint-link structures, metal components that wrapped around each finger segment were sewn on to the glove. Thus a metal component was sewn on to the glove between the knuckle joint and the 2nd joint of the finger and from the 2nd joint to the 1st of the finger. The joints were specifically not covered with metal components to allow for full range of motion from the fingers of the user and maximize comfort. To maximize comfort, the metal components that wrapped around each finger segment were made with two L-shaped bracket pieces bolted together to form a rectangle that fits over the finger segment. The attachment site at which the bolts are located to bolt the two brackets together are not circular in shape but long oval shapes. As a result, the width of the rectangle can be easily adjusted to the width of the finger of the user.

The link-joint-link structure was attached to the rectangular metal components with spacers in between. The cable would pass through the two links as shown in figure 12. The spacers allow for spacing between the link-joint-link structure and the finger of the user to allow for the cable to slide freely.

The link-joint-link structure of the knuckle joint was implemented slightly differently. The challenge for the knuckle joint was that unlike fingers where they are detached from the main body of the hand and allow for components to be wrapped around the finger, the knuckle joint is a part of the body of the hand and thus, components could not be wrapped around each knuckle joint individually. If the knuckle joints were treated individually, the only choice would be to place the link-joint-link structure on top of the knuckles on the back of the hand. This would be extremely bulky. The solution approached in this design was to treat the knuckle joint as one joint. The finger segment between the knuckle joint and the 2nd joint of the last three fingers were attached to a metal bar. Another bar was attached to the palm of the hand. To lock the knuckle joint in place, the position of these two parts must be locked in position. Angle brackets were connected at the end of each metal bar, which was then connected to the link-joint-link structure on both sides of the metal bars. Cable was then passed through each link to complete the cable loop lock mechanism. Refer to the section on design procedures for diagrams.

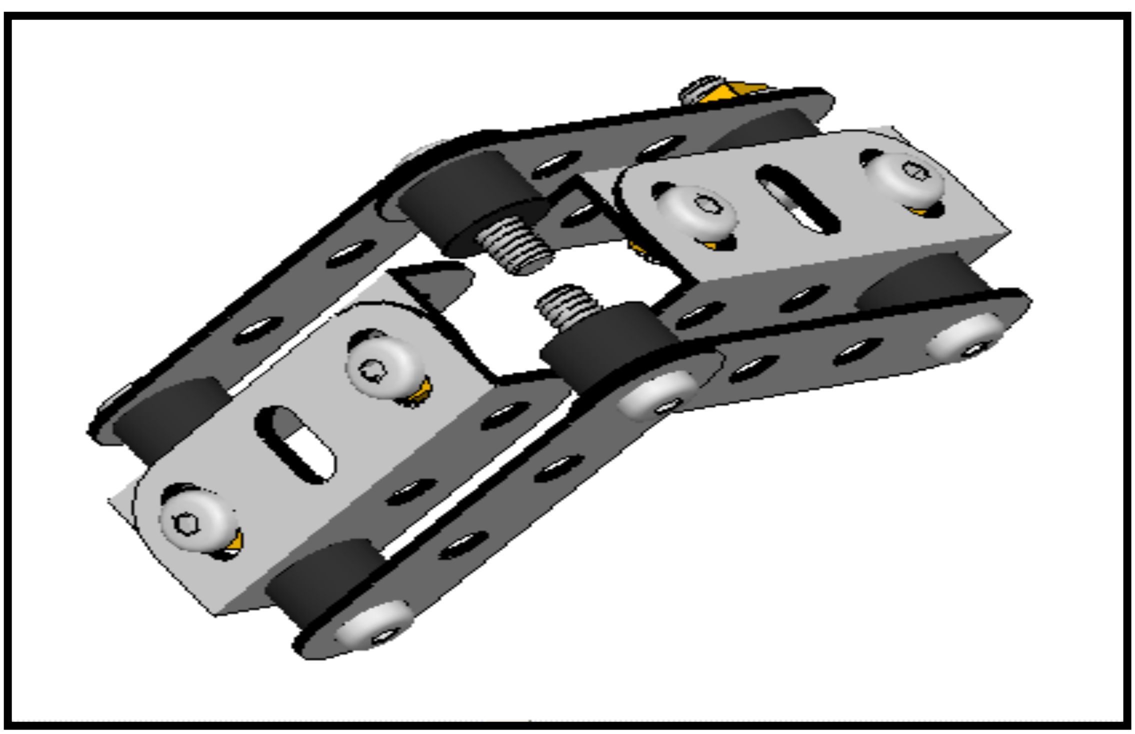


Figure 14 - CAD Drawing of Exoskeleton for 3rd Finger

2.3 Feedback to User

To implement safety controls, feedback is sent back to the user to warn the user of the actuation of the exoskeleton. This is the done through the activation of a DC buzzer for audio, an LED (visual), and a vibrating motor (sense even without looking at the exoskeleton) before the activation of the solenoid to activate the lock mechanism. Thus, the 3 together act as a warning mechanism to the user. A delay is input between the time of the warning signal and the time of actuation of the solenoids to allow for the user to manually turn off the exoskeleton through the "kill" switch. The kill switch can be activated at any time if the user decides to override the exoskeleton's decision to actuate the solenoids and turn off the locking mechanism.

CHAPTER 3

Design Procedures

This section will go over the design procedures to make the exoskeleton glove following the methodology of solution outlined in chapter 2. Each section will be described individually including data acquisition and analog signal conditioning, control software, and the physical hardware.

3.1 Data Acquisition

Data acquisition involves the acquisition of force and flex signals from the user.

Parts used:

2 Interlink 0.5” diameter circular FSR (Force Sensing Resistor) 26

1 Spectra Symbol 4.5” Flex Sensor

1 Velcro tape

Velcro backing was applied to each of the sensor as well as to the parts on the glove to where the sensors would be attached. The Velcro backing allows for each adjustment of the placement of the sensors to fit to the individual user’s hand and power grasping pressure points on the fingers. The location of the sensors which are all located on the palm side of the hand are shown in figure 15.

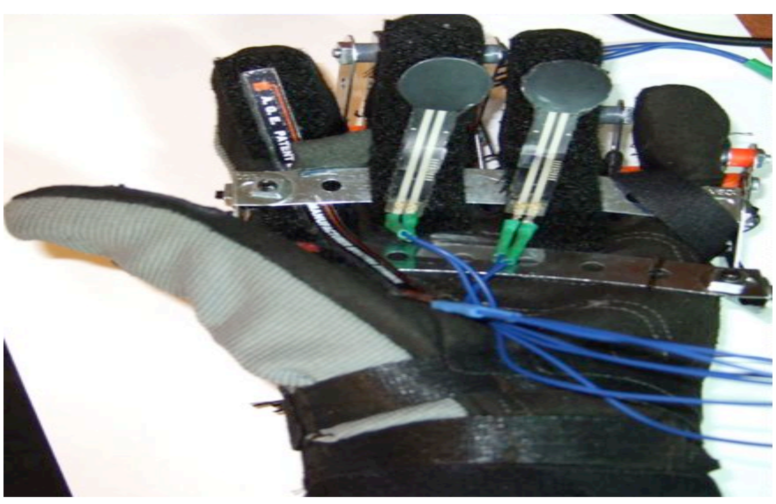


Figure 15 - Force and Flex Sensors Placement (Flex sensor shown on 2nd finger, force sensors shown on 3rd and 4th fingers)

As shown in figure 15, the flex sensor is placed vertically along the 2nd finger and the force sensors are located on the fingertips of the 3rd and 4th fingers. The ends of each sensor consists of two metal connectors that are soldered on to wires which are attached to the control (analog signal conditioning) as inputs which is described in the next section.

3.2 Analog Signal Conditioning (Control Circuitry)

This part of the exoskeleton converts the signals from force and flex sensors into voltage signals and interfaces the sensors to the analog inputs of the microcontroller. Output components including the solenoids, vibrating motor, DC buzzer, as well as LED are connected to the digital outputs of the microcontroller.

Microcontroller

The microcontroller used is the arduino nano. The schematic of the arduino nano showing the location of the digital input and output pins are shown in figure. 16.

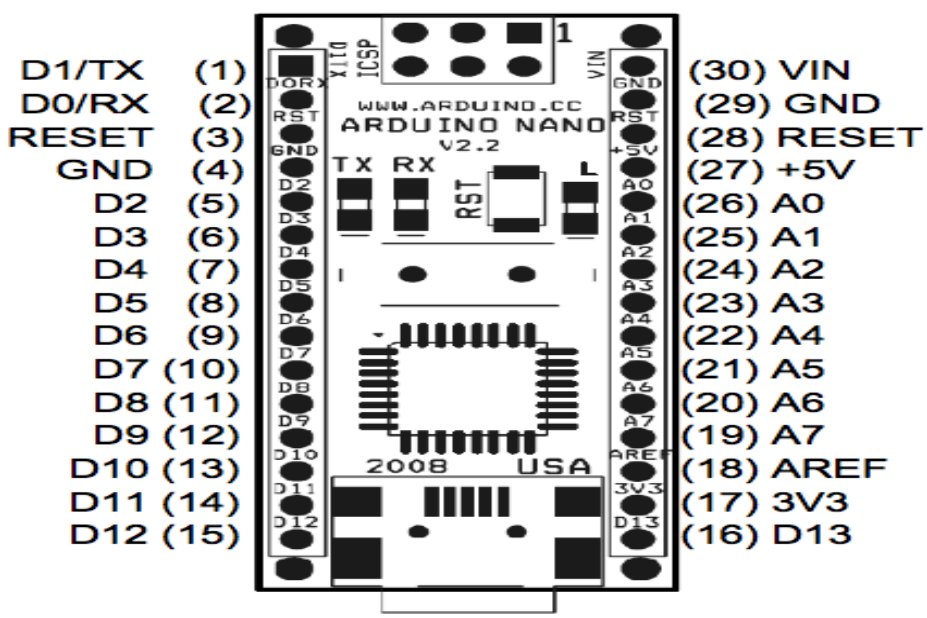


Figure 16 - Schematic Showing Layout of Pins on the Arduino Nano

The D0 – D13 correspond to the digital input/output pins. The digital pins either receive a high (5 V) or low signal (0 V) and are converted to a 1 or 0 in the microcontroller. As an output digital pin, the pin either outputs high (5 V) or low signal (5 V). The inputs to the analog pins of the microcontroller is an ADC and converts the signal at the input (can range from 0 to 5 V) to a number between 0 and 1024.

Input to the Microcontroller

The input to the microcontroller includes interfacing the force and flex sensors to the analog inputs of the microcontroller. The force and flex sensors are variable resistors and are each placed in a voltage divider as shown in figure 17 and then connected to the input of the microcontroller.

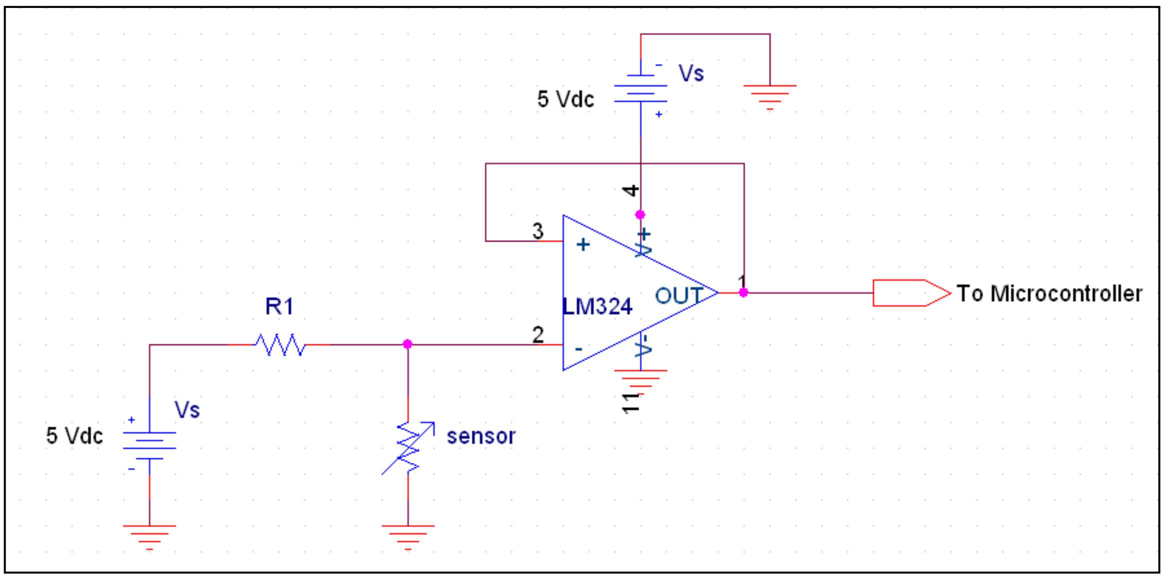


Figure 17 - Voltage Divider Network To Convert Sensor SIgnals to Voltage Signals

The output of the voltage divider from one of the force sensors (fsr 1) is connected to input pin D2. The output of the voltage divider network from fsr2 is connected to input pin D3. The flex sensor is connected to input pin D7.

Resistor values:

For fsr’s, R1 = 2 kΩ

For flex sensor, R1 = 25 kΩ

Output from the Microcontroller

Led, buzzer, vibrating motor, and 2 solenoids are connected to the digital output pins from the Microcontroller.

LED: Connected from D13. A series resistor of 1 kΩ is placed in front of the led to lower current passing through LED.

Buzzer: Connected from D4.

Vibrating Motor: Connected from D12. A diode is placed in series to the vibrating motor to drop voltage across vibrating motor.

Solenoid1: Connected from D7 to input of driver circuit shown below in figure 18.

Solenoid2: Connected from D10 to input of driver circuit shown below in figure 18.

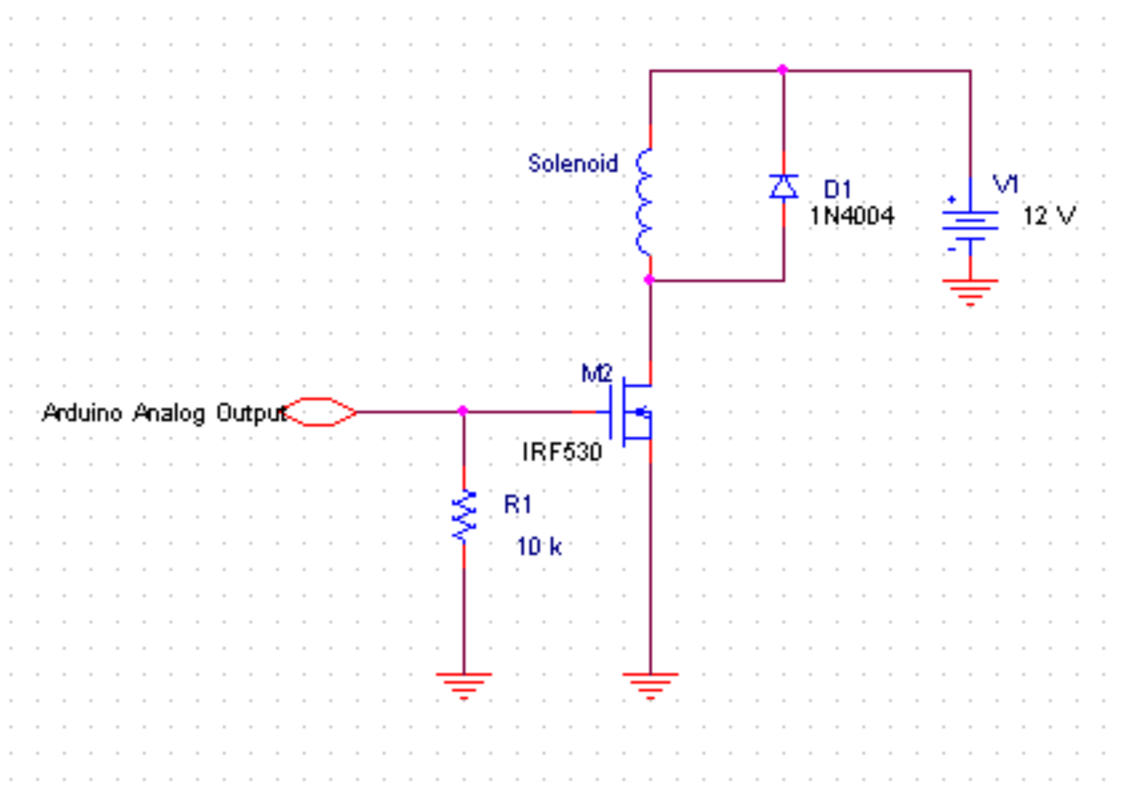


Figure 18 - Driver Circuit for Solenoid

Power Supply

The arduino nano is powered with a 12 V battery. The solenoids as can be seen from figure 18 are powered from the same 12 V battery.

3.3 Control Software

Basic Microcontroller Logic

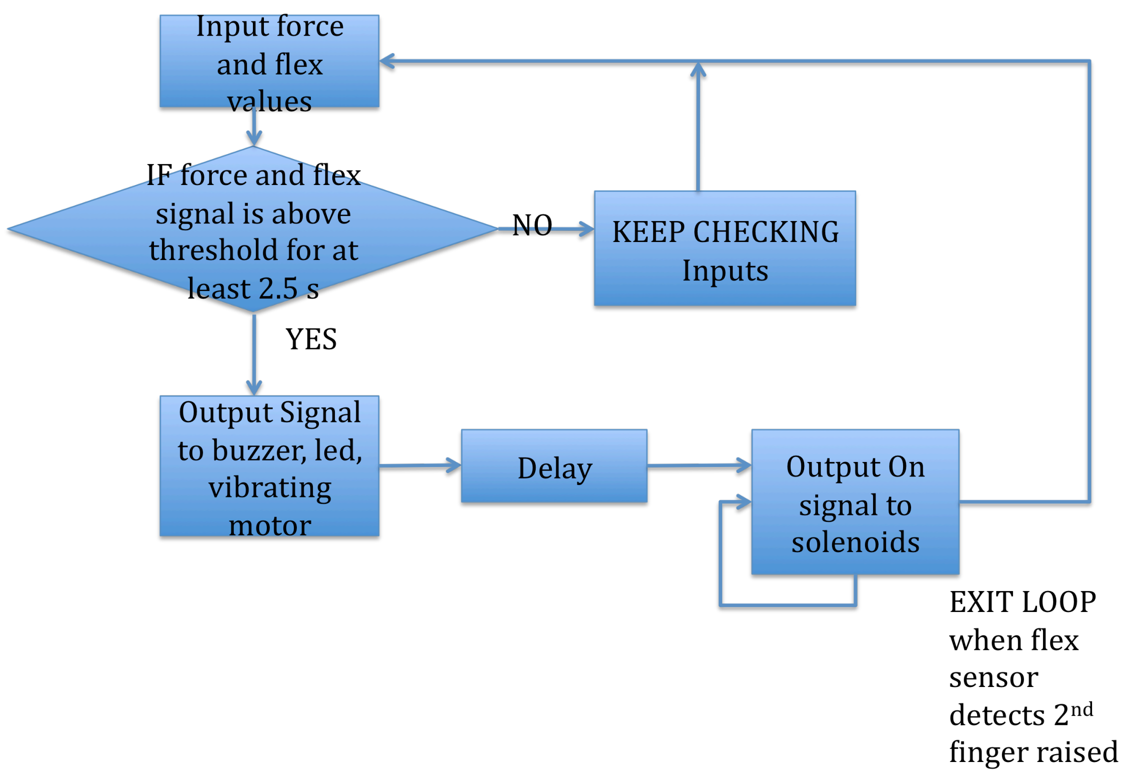


Figure 19 - Basic Program Logic Implemented in Arduino Nano

The above program logic is implemented in the arduino nano with the following program:

```
//Exoskeleton Code

#define BUZZER 4
#define VM 12
#define LED 13
#define SOLENOID 7
#define SOLENOID2 10
int fsr1, fsr2, flex = 0;
```

```
int flag = 0;

void setup()
{
  pinMode(BUZZER,OUTPUT);
  pinMode(VM,OUTPUT);
  pinMode(LED,OUTPUT);
  pinMode(SOLENOID,OUTPUT);
  pinMode(SOLENOID2,OUTPUT);

  Serial.begin(9600);
}

void loop(){
  flag=0;
  fsr1 = analogRead(2);       //read in inputs
  fsr2 = analogRead(3);
  flex = analogRead(7);
  Serial.println(flex);
  if(fsr1<=700 && flex>=540){    //check if inputs pass threshold values
    delay(2500);
    fsr1 = analogRead(2);        //makes sure input is sustained for at least 2.5 s
    fsr2 = analogRead(3);
    flex = analogRead(7);
    if(fsr1<=700 && flex>=540){
      digitalWrite(BUZZER,HIGH);  //output to solenoids, led, buzzer, motor
      digitalWrite(VM,HIGH);
      digitalWrite(LED,HIGH);
      delay(1000);
      digitalWrite(BUZZER,LOW);
      digitalWrite(VM,LOW);

      while(flag==0){            //exit when flex sensor senses raised finger
        digitalWrite(SOLENOID,HIGH);
        digitalWrite(SOLENOID2,HIGH);
        flex = analogRead(7);
        if(flex<=500){
          delay(1000);
          flex = analogRead(7);
          if(flex<=500){
            flag=1;
          }
        }
      }
      digitalWrite(SOLENOID, LOW);
      digitalWrite(SOLENOID2,LOW);
```

```
    digitalWrite(LED,LOW);
   }

 } else {      //else if threshold values are not met,  output low to buzzer, LED, motor,
and solenoids
  digitalWrite(BUZZER,LOW);
  digitalWrite(VM,LOW);
  digitalWrite(LED,LOW);
  digitalWrite(SOLENOID,LOW);
  digitalWrite(SOLENOID2,LOW);
 }
}
```

3.4 Physical Hardware (Actuators, Locking Mechanism, and Physical Structure of Exoskeleton Glove)

This section will outline the physical construction of the exoskeleton glove. The basic construction procedure begins with the construction of the link-joint-link structure for joint. These structures are sewn on to go the glove. Once the link-joint-link structures are on to the glove, cables are looped through the links of the link-joint-link structures to form the cable loop lock mechanism. After, the solenoids are attached to the back of glove and the cables are attached the plunger of the solenoids.

Link-Joint-Link Structure

The link-joint-link structures are all constructed from meccano and a cad drawing of each of the figures is shown below. An overview view of the structure is shown. Top, side, and bottom views are shown in the appendices.

3^{rd} Finger – 2^{nd} Joint:

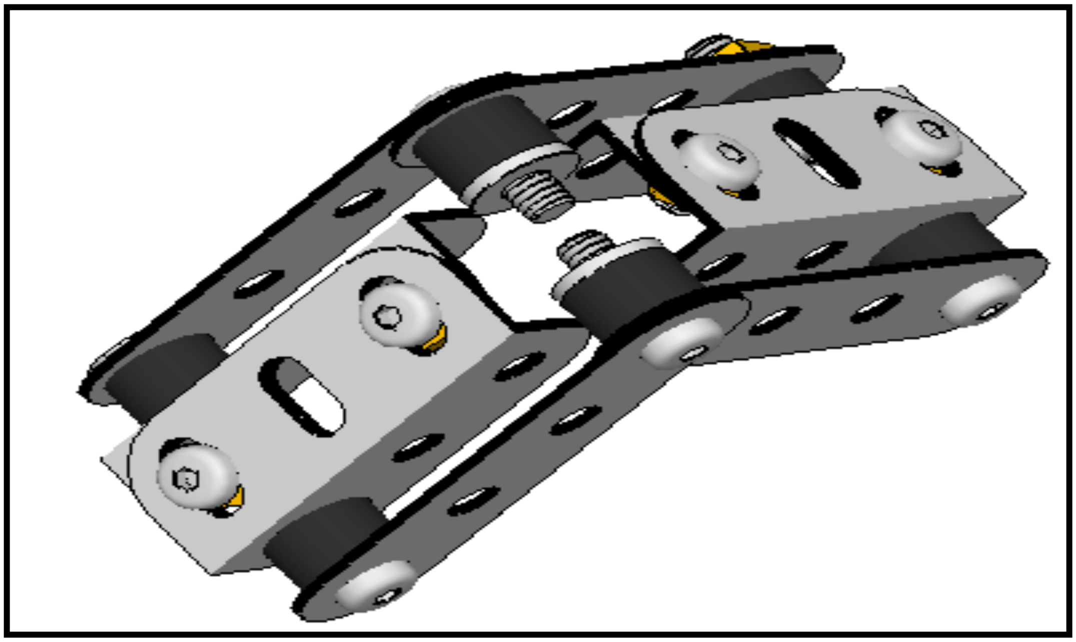


Figure 20 - Link-Joint-Link Structure for 2nd Joint on 3rd Finger

4th Finger – 2^{nd} Joint:

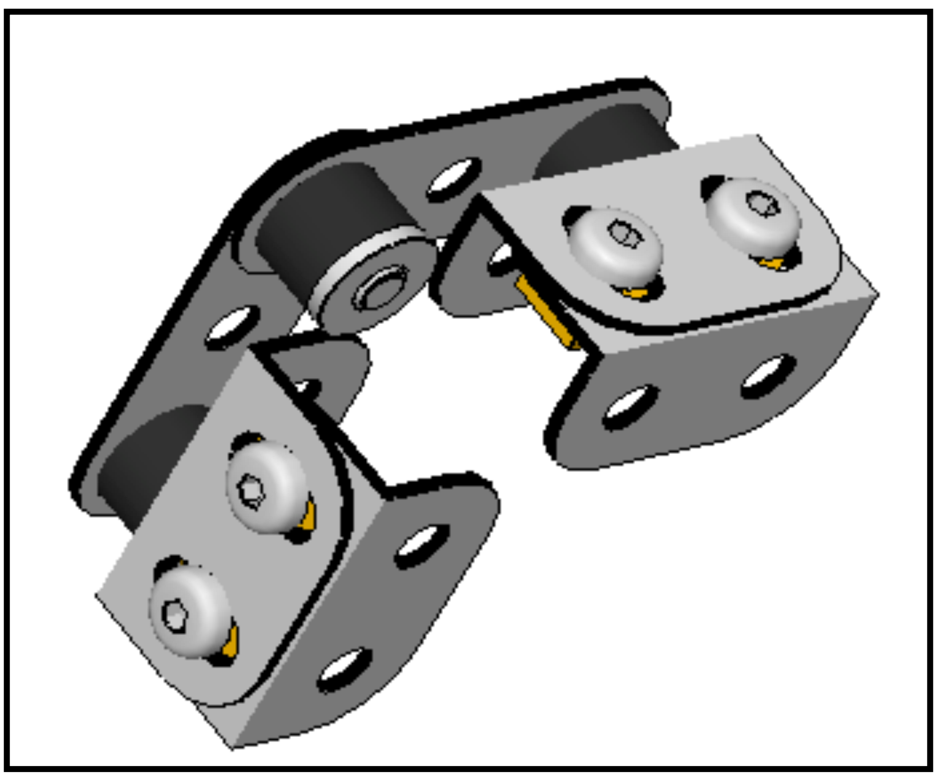


Figure 21 - Link-Joint-Link Structure for 2nd Joint on 4th Finger

4th Finger – 2nd Joint:

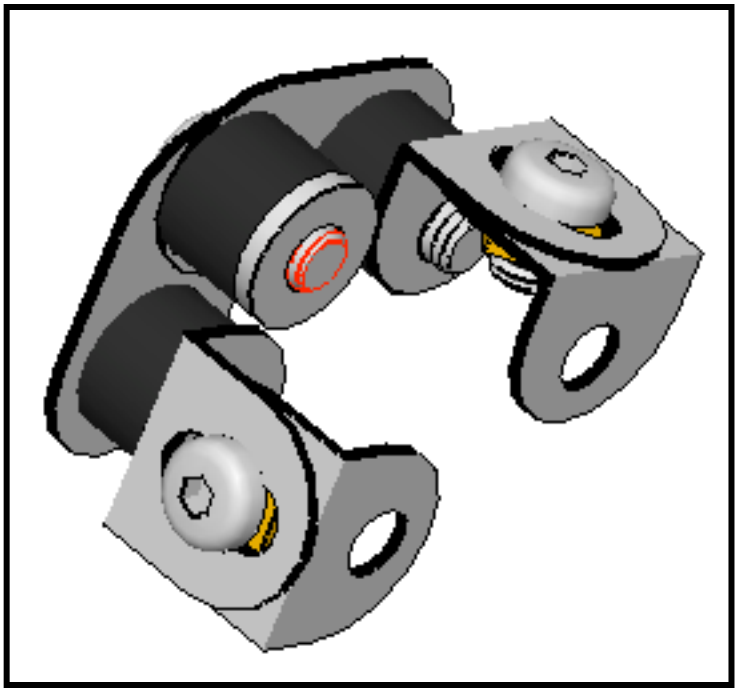


Figure 22 - Link-Joint-Link Structure for 2nd Joint on 5th Finger

Each of the link-joint link structures for the 2nd joint wrap around each finger and don't sit on top of the finger. The joint of the link-joint-structure should line up with the joint of the user finger. Also, for readjustment to fit the user's size, the width of the structure can be adjust be loosening the bolt that attaches the two L-shaped brackets for each finger segment. The structure is sewn on to the glove through the holes of the meccano pieces.

Knuckle Joint:

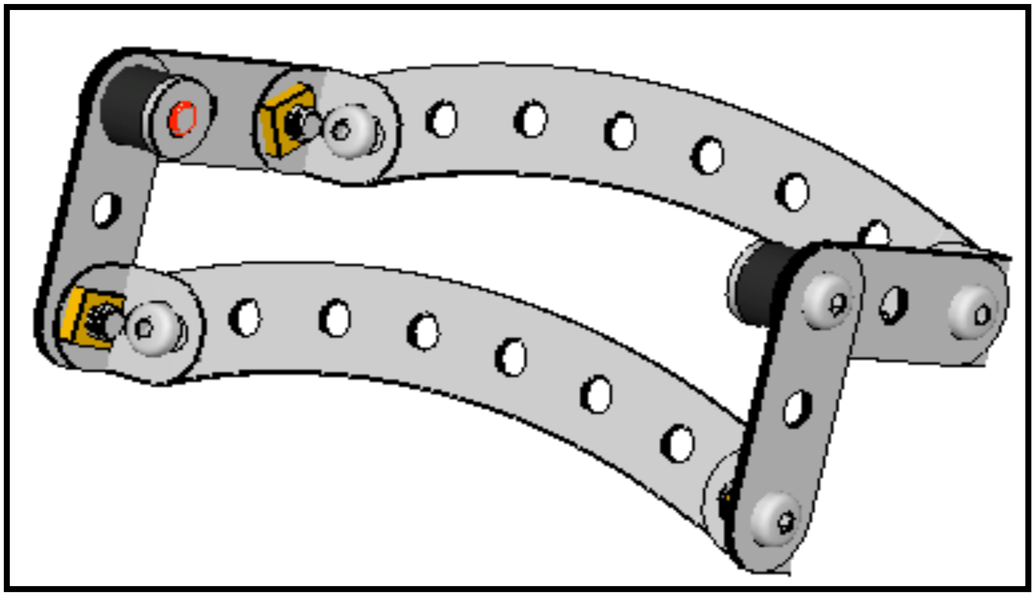


Figure 23 - Link-Joint-Link Structure for Knuckle Joint

The knuckle joint is slightly different than the joints shown for the 2nd joints of each finger. The two bars connecting the two link-joint-link structures are shown in figure 23 are sewn on to the palm of the glove. It is important to have one of the bars on the segment of the fingers between the knuckle and the 2nd joint. The other bar should be placed as far as possible on the palm. Again, the structure is sewn on to the glove through the holes of the meccano pieces.

Attaching Cables

For the cable, a type of fishing line is used: Braided tip-up line. It was chosen as it has low stretch and can also withstand high tensions of up to 20 lbs (9 kg) which is above the tension requirements of the exoskeleton glove. To form the cable loop around each link, a loop is first formed by bending a single string in half and knotting the ends of the 2 loose ends. The cable loops is then formed as shown in figure 24.

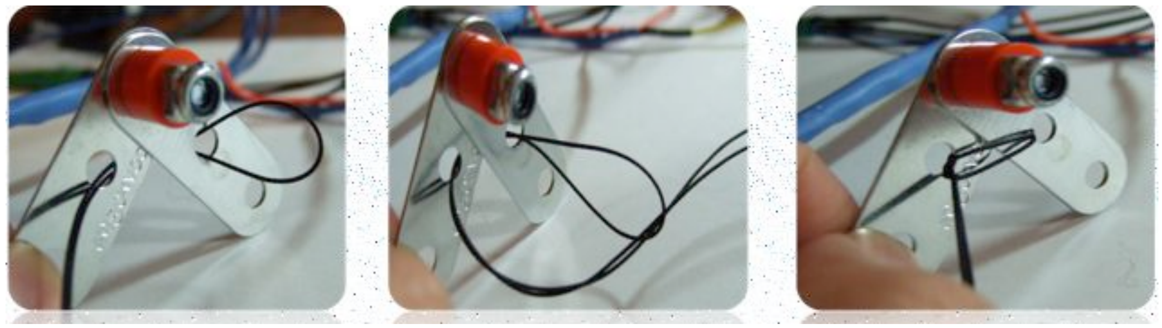


Figure 24 - Cable Loop Forming Procedure

This is done for each link-joint-structure.

Attaching Solenoids

Each solenoid is placed in a plastic motor clip holder as shown below in figure 24.

Figure 25 - Plastic Motor Clip Holder Used to Hold Solenoid

Velcro backing was placed on the back of the clip and also on to the back of the glove where the solenoids are to be placed. To secure the solenoids in place, Velcro strips are sewn on to the palm side of the glove and wrapped around the solenoids from the right side of the hand and attached on the left. The user straps on the Velcro after he/she wears the glove. Cables are then attached to the plunger of the solenoids. The placement of the solenoids and the length of the cables is very important. To properly calibrate the cable loop lock mechanism, the length of the string must correspond to the following situation: when the plunger of the solenoid is fully pulled in (stroke length = 0), and the user is gripping as tightly as possible (smallest joint angles), the cable must be full outstretched. The method in attaching all the loose ends of the cable to equally actuate all fingers was described in the methodology of solution section 2.2 figure 13.

The final exoskeleton should look like that shown in figure 25.

Figure 26 - Final Exoskeleton Glove

CHAPTER 4
Experimental Procedure

In this section, a testing procedure was completed to test the holding force of the cable loop locking mechanism. It is also compared against the holding force of the cable tension system.

4.1 Testing Apparatus

A blown up model of the link-joint-link structure that exists throughout the exoskeleton was built as shown in figure 26.

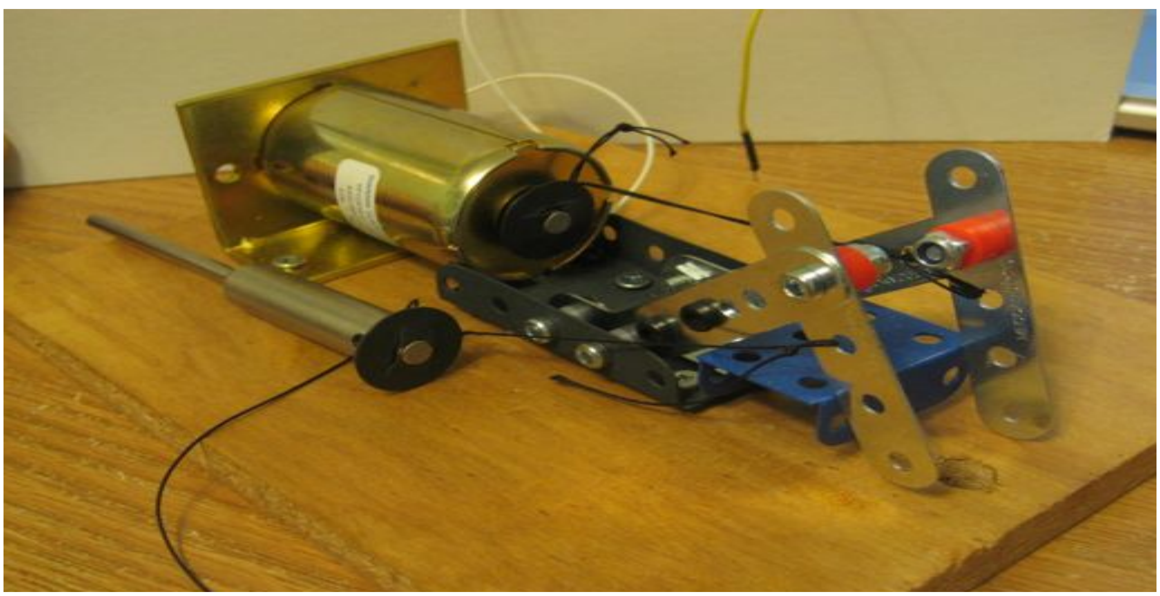


Figure 27 - Model of Link-Joint-Link Structure

As seen in figure 26, two link-joint-link structures were built each with a cable attached to the links attached to a plunger that can be placed in the solenoid. One of the structures used the cable tension system whereas the other structure used the cable loop system as shown in figure 27.

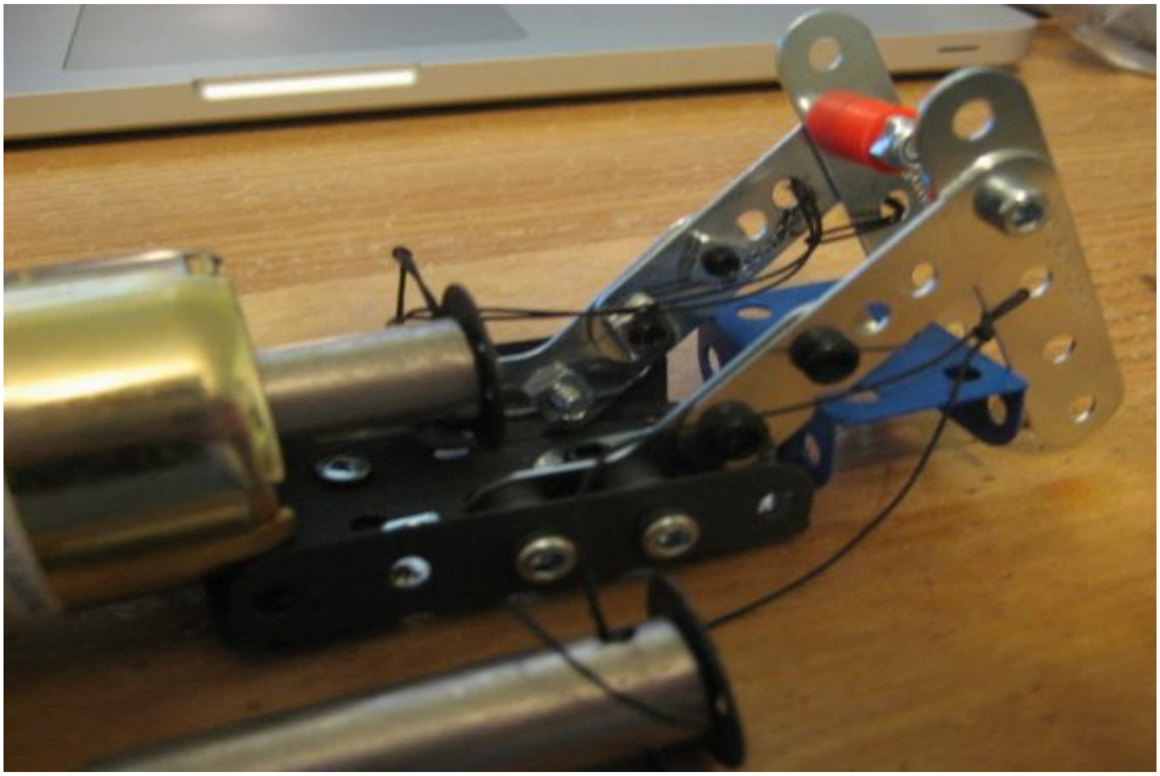


Figure 28 - Cable Loop (left structure) vs Cable Tension (right structure)

To test the holding force of each system, 12 V was applied across the solenoid which would actuate the solenoid and cause the plunger to be pulled in and locking position of the links. A spring scale was hooked on to the link and pulled. The force at which the links moved was recorded. The testing apparatus is shown in figure 28 The holding force for both tight (small joint angle) and large (large joint angle) grip were tested. A tight grip is one where the stroke length is 0 cm. A large grip is one where the stroke length is 0.3 cm. The large grip was simulated by placing spacers between the plunger and the solenoid such that a stroke length of 0.3 cm was achieved. The solenoid used was a continuous solenoid with a holding force of 5 lbs.

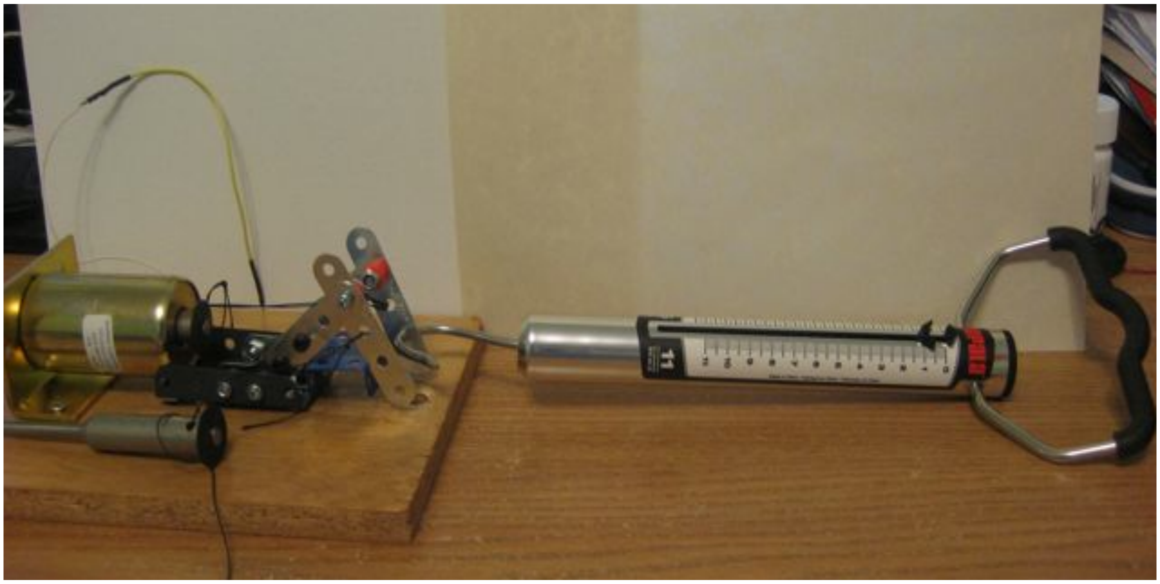


Figure 29 - Testing Apparatus for Testing Holding Force of Cable Tension System Vs Cable Loop System

CHAPTER 5

Results and Discussions

The results of the testing experiment described in chapter 4 is shown here.

Results of Holding Force for Cable Tension System

Table 4 - Stroke Length and Corresponding Holding Forces for Cable Tension System

Stroke Length	Holding Force (lbs)
0 cm (tight grip)	3.7
0.3 cm (large grip)	1.3

Results of Holding Force for Cable Loop System

Table 5 - Stroke Lengths and Corresponding Holding Force of Cable Loop System

Stroke Length	Holding Force (lbs)
0 cm (tight grip)	> 15
0.3 cm (large grip)	8.8

In table 5, the holding force at 0 cm is >15 lbs because the cable broke at 15 lbs before the link could be moved.

The results above clearly show that the holding force of the cable loop system is much higher than that of the cable tension system by at least approximately 7 times. Also, the solenoid rated holding force was 5 lbs. The cable tension system had a maximum holding force of less than 5 lbs. However, the maximum holding force of the cable loop system was much greater than 5 lbs. Although the maximum holding force could not be measured since the cable broke at 15 lbs, the maximum holding force of the cable loop system was at least 15 lbs. Thus, the cable loop system successfully added holding force to the system. This large increase in holding force is mainly due to the friction create the cable against one another. In order for the links to move with respect to each other, the loop must become larger and in order for this to happen, the cables must slide past each other. When a slight force is applied to the loop by pulling, the cables are now compressed with respect to each other. This can be imagined by placing a cable in a small notch. This creates a very high friction situation in order for the cable to move at even small forces applied to the system. As a result, with 5 lbs of holding force applied from the solenoid itself, it can be seen that the cable loop system can provide much greater than 5 lbs of holding force.

CHAPTER 6

Conclusions and Future Improvements

6.1 Conclusion

The design of the exoskeleton glove was able to achieve the main goals outlined in section 1.2 Detection of a power grasp was successfully implemented by combining flex sensors and force sensors. Regular contact forces would not be able to activate the exoskeleton. Feedback to the user was implemented as well as a safety mechanism where the user can override the actions of the exoskeleton at any time. The physical structure of the exoskeleton was successfully designed to be as compact as possible with all elements of the glove (locking mechanism, actuators, and physical structure) to fit on one hand. The physical structure also satisfied the criteria of not causing discomfort to the user by being an adjustable structure as well as closely mimicking the finger joint motion of the user with the adjacent link-joint-link structure with the structure not covering the joint. The structure also did not place excessive forces on the fingers of the user as the maximum joint angle that the exoskeleton can enforce is controlled by the length of the cable which is calibrate for each user to only enforce a joint angle up to the tightest grip of the user. Most importantly, the exoskeleton was able to have a maximum holding force much beyond 5 lbs where the maximum holding force was at least 15 lbs and was able to successfully lock the joint position. The cable loop mechanism proved to be a much better system than the cable tension system with holding forces 7 times higher than the cable tension system. The cable loop locking mechanism proved to be key as it not only provided more holding force but the nature of the mechanism allowed for short actuation distances which allowed for the use of small solenoids which can only provide high holding forces over short distances. This enabled the solenoids to be mounted on the hand as well.

6.2 Future Improvements

Future improvements could be made to the force sensors used in the exoskeleton glove as well as to the actuation system itself. The force sensors used (Interlink FSRs) seemed to be extremely fragile with a very short actuation lifetime. The force sensors did not appear to work with applications that require much bending around the force sensors causing them to break down. Future improvements would be to look into other force sensors such as the flexiforce sensors from Tekscan.

To save costs for this project, it was opted to only use 2 solenoids to actuate all of the 2nd joints of each finger and another solenoid to actuate the knuckle joint. This design was feasible due to the equal actuation distances for each individual joint. However, due to the different distances and angles between the exoskeleton joint and the solenoid itself, it proved to be very difficult to calibrate the system such that the solenoid caused equal displacement for each joint. For future improvements, the best option would be to have one solenoid actuate each individual joint. This will create a much more accurate and stronger locking mechanism for each joint.

Further improvements would be to minimize the physical structure of the exoskeleton glove even further by moving beyond the prototyping stage of meccano pieces to lighter, stronger materials that are not as bulky.

APPENDICES

Table – Corresponding Force and Resistance Values Measured from Interlink FSR (force values from 200 g to 2 kg) Trial 2

Force (g)	Resistance (kΩ)
200	5.6
400	2.6
600	2.1
800	1.6
1000	1.3
1200	1.15
1400	1.03
1600	0.96
1800	0.84
2000	0.75

Table – Corresponding Force and Resistance Values Measured from Interlink FSR (force values from 200 g to 2 kg) Trial 3

Force (g)	Resistance (kΩ)
200	6.2
400	3.1
600	2.1
800	1.5
1000	1.2
1200	1.03
1400	0.95
1600	0.84
1800	0.74
2000	0.72

Pontiac Coil
2110 Queensway Searcy, AR 72143
Phone 501-268-6877 Website: www.pontiaccoil.com

Model L-75 DC Solenoid Tubular, Pull Type

Pontiac Coil - Arkansas is an ISO 9001:2000 Certified Company

*Resistance values are ± 10% at 25°C

Model Code	Part No.	Voltage	Duty Cycle	Power (W)	Resistance (Ω)*	Current (A)
L-75PL012D-C-2	F0471A	12VDC	Continuous	6	23.0	0.6
L-75PL012D-I-2	F0472A	12VDC	Intermittent	40	3.6	3.4
L-75PL024D-C-2	F0473A	24VDC	Continuous	6	88.3	0.3
L-75PL024D-I-2	F0474A	24VDC	Intermittent	40	14.4	1.7

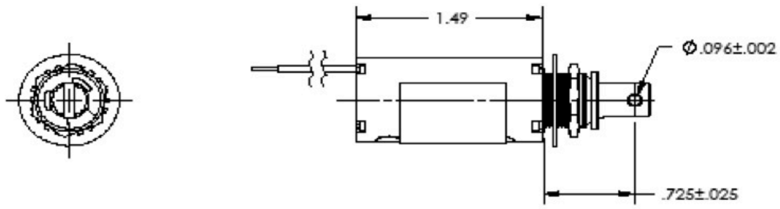
Definition of Duty Cycles:

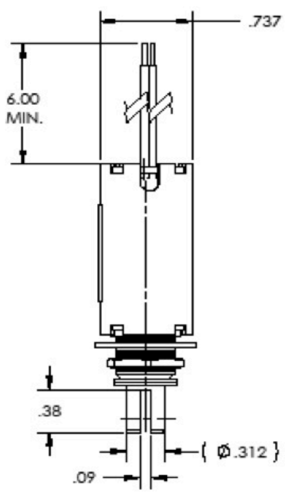
Continuous = indefinite activation; **Intermittent** = 1 minute ON and 3 minutes OFF; **Pulse** = 100 msec. ON and 900 msec. OFF

Special order options: 6 to 48 Volts, DC only; push-type configuration. Consult factory for other modifications.

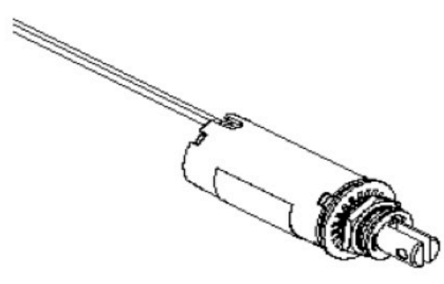
Stroke (in.):	Sealed	1/16	1/8	1/4	3/8	1/2	5/8	3/4
Cont. Duty force	63 oz.	28 oz.	14 oz.	6 oz.	3 oz.	2.5 oz.	N/A	N/A
Int. Duty force	84 oz.	64 oz.	46 oz.	28 oz.	20 oz.	14 oz.	11 oz.	6 oz.

Typical force values when operated at 100% rated voltage at 25°C. Derating required for lower voltage and higher temperature.





Solenoid supplied with 9/16" hex panel nut
15/32-32 UNF 2B thread



Solenoid shown energized, with plunger seated

Insulation Materials: UL Construction, Class B 130°C

Copper magnet wire insulation rated 155°C (class F)

Voltage Breakdown Strength: 1500 VAC RMS Life Expectancy: 10 million operations

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