EE 4BI6 Electrical Engineering Biomedical Capstones

Department of Electrical and Computer Engineering

4-23-2010

Design of a Forearm Exoskeleton for Supination/Pronation Assistance in Daily Activities

Michelle Ngai
McMaster University

Recommended Citation

Ngai, Michelle, "Design of a Forearm Exoskeleton for Supination/Pronation Assistance in Daily Activities" (2010). *EE 4BI6 Electrical Engineering Biomedical Capstones.* Paper 53.
http://digitalcommons.mcmaster.ca/ee4bi6/53

Design of a Forearm Exoskeleton for Supination/Pronation Assistance in Daily Activities

By

Michelle Ngai

Electrical and Biomedical Engineering Design Project (4BI6)
Department of Electrical and Computer Engineering
McMaster University
Hamilton, Ontario, Canada

Design of a Forearm Exoskeleton for Supination/Pronation Assistance in Daily Activities

By

Michelle Ngai

Electrical and Biomedical Engineering
Faculty Advisor: Prof. Doyle

Electrical and Biomedical Engineering Project Report
submitted in partial fulfillment of the degree of
Bachelor of Engineering

McMaster University
Hamilton, Ontario, Canada
April 23, 2010

ABSTRACT

With the growing aging population, there is an increasing demand and opportunity to develop exoskeletons, which are typically designed for military or industrial use, to be used on a daily basis to provide power assistance. Such exoskeletons could be used by the physically impaired and injured, in addition to the elderly.

This report describes the design of a power-assist exoskeleton specifically for the pronation and supination motion of the forearm. The exoskeleton is controlled by two push-button sensors to indicate the direction of rotation, which is controlled by the user at all times. As a safety precaution, visual feedback was implemented to confirm the user's inputs were received by the exoskeleton and that the robot is actuating. A stepper motor, whose torque is transferred to the system using a bidirectional winch system, is used such that the exoskeleton is able to output such holding torques to lock the position of the arm. The mechanical structure is composed of various PVC and ABS coupling hubs, which form a stationary and rotating unit. The exoskeleton is fixed onto the user's forearm through a blood pressure cuff, and torque is transferred from the motor to the user's wrist through a custom-carved Styrofoam wrist cuff.

From testing, the average running torque of the system ranged from 5.24 Nm to 9.17 Nm for motor speeds from 60 rpm to 45 rpm, respectively, which confirmed that decreasing motor speeds increased running torque. The amount of holding torque could not be quantified because the testing setup was unable to produce sufficient loads (>55Nm) to move the system out of its fixed position. However, when in "idle", the system still produced a holding torque of 30 Nm, suggesting a significant source of torque transfer loss in the system.

The exoskeleton was worn by a user and tested for comfort, usability and overall functionality. While there were a few sources of discomfort that were expected, the robot was able to actuate the proper motions for the user and provide powered assistance.

Overall, the system was able to pronate, supinate and hold the user's forearm as controlled, demonstrating that the exoskeleton successfully provided powered-assistance.

Keywords: exoskeleton, power-assist, pronation, supination, wearable robot

ACKNOWLEDGEMENTS

I would like to thank my partner, Regina Leung, for her support, determination and enthusiasm throughout the year.

I would as like to thank Dr. Doyle for his guidance and advice in this project.

Finally, thanks to my family for their support as always.

Michelle Ngai

TABLE OF CONTENTS

1 Introduction

2 Literature Review

3 Statement of Problem and Methodology of Solution

4 Experimentation and Design Procedure

5 Testing – Results and Discussion

6 Conclusions and Recommendations

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1:

INTRODUCTION

1.1 Background

An exoskeleton is wearable biomechatronic system/robot that transmits power to the limb or body of the user on which it is worn. There are exoskeletons currently being developed which are primarily targeted for military/industrial applications [1] (full-bodied, load-bearing) and rehabilitation [2] [3] [4] (low mobility, high precision). Since the elderly population (those over 65 years old) has increased to approximately 20% [5], there is an opportunity to develop an exoskeleton specifically for the hand and wrist to provide power for day-to-day motions. Additionally, the proposed exoskeleton can be used by those who have suffered from a wrist or hand injury that causes weakness in grasping or supination/pronation. As grasping and wrist pronation/supination are regularly used in everyday activities, being able to reinforce these movements will be significantly beneficial to the user's quality of life and independence.

1.2 Objectives and Scope of the Project

The objective of this project is to design and build an exoskeletal device that assists the user by supplying additional power in day-to-day activities that involve grasping and forearm supination/pronation. The targeted user is someone who has weakened hand or wrist movements due to age or injury (i.e. Carpal Tunnel Syndrome). While rehabilitation exoskeletons are focused on generating a range of motions in a precise manner, this device focuses on providing strength/reinforcement in typical motions, following the user's natural movement.

There are many sophisticated exoskeletons being developed in research and industry. The goal of this project was to design and implement a simple solution that performs the same functions on a smaller scale. The end product should be one that is intuitively and reliably controlled such that other motions are not inhibited or impeded, relatively compact in size, safe and cost-effective. In the operation of the forearm exoskeleton, the device should be able to aid in the supination and pronation motion, as well as hold the position for the user.

The exoskeleton is intended for power assistance in daily activities. As a result, the speed and torque output of the robot is designed to be at a moderate level. Since it is a power-assistive device, the robot should be worn on the non-dominant hand to allow for the dominant hand to perform precise movements.

One of the main factors that was constantly considered throughout the design and implementation process was ensuring the solution would be physically realizable. Because of this, several revisions and redesigns were required.

1.3 General Approach to the Problem

This project was divided into two subprojects: a hand exoskeleton for grasping and a forearm exoskeleton for pronation/supination. While each exoskeleton was designed and implemented as completely independent systems, considerations were made throughout the design process with the intention of combining the two robots together for simultaneous operation.

This report describes the design of the forearm exoskeleton.

CHAPTER 2:

LITERATURE REVIEW

2.1 Anatomy and Biomechanics

In order to determine the target values for the exoskeleton in terms of output torques, research was done to find out how much torque an average person could generate when supinating and pronating. From a study by O'Sullivan and Gallwey, it was determined that the mean maximum torque (using different elbow positions) for supination and pronation was 16.2 Nm and 13.1 Nm [6], respectively. It is important to note that the experiments were performed using 25-year-old male subjects. These values are much higher than required for the exoskeleton, but they are useful to know as a point of reference.

2.2 Current Upper-Limb Exoskeletons

To get an idea of the current status of exoskeletons in terms of abilities and sophistication of the systems, we examined a number of research projects including the RiceWrist [7] and a series of exoskeletons developed at Saga University by Kazuo Kiguchi [8], [9]. One paper discussed the state-of-the-art and design difficulties of mechanical systems, which also compared many different exoskeletons with details on the types of actuators, power transmission method, etc. [10]

From research into current upper-limb exoskeletons, we observed that the solutions presented seemed very large, bulky and importable. This is most likely due to the fact that upper-limb exoskeletons are mainly still in the research stage (in comparison to lower-limb or full-body exoskeletons, which are much further developed) [1] and were not implemented in a realistic manner for everyday use.

From the 6DOF upper-limb exoskeleton [8], the range of motion expected for pronation and supination is 60^o and 80^o respectively, as depicted in Figure 1 [8].

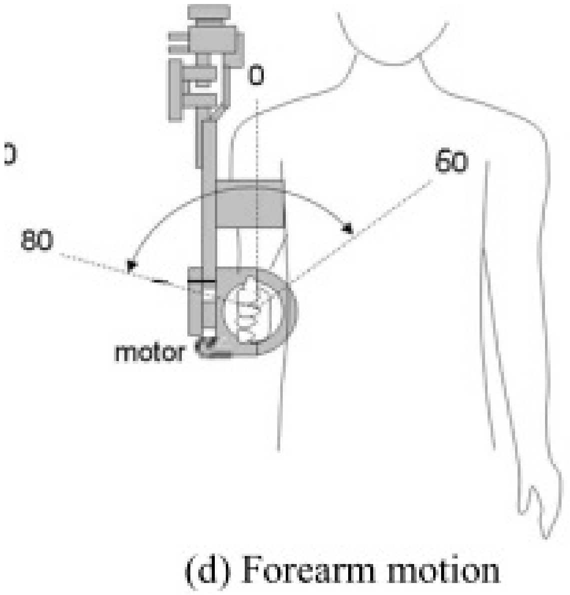


Figure 1 – Range of motion for pronation and supination

2.3 User Interface: Input Control Method

One of the first design decisions that had to be made was input control method. Most of the exoskeletons we came across used an EMG-based control, which involved extracting the myoelectric signals from the muscles using surface electrodes to control the exoskeleton after the signals are interpreted as intention for movement. However, there are many difficulties involved with using EMG control [9].

- There are many muscles within the forearm, which is a small, confined volume. As a result, there is always crosstalk between signals of neighbouring muscles. It is often difficult to distinguish the EMG signal for each muscle.
- Each muscle is involved with multiple activities. Even if the EMG signals can be isolated for the muscle, the controller cannot determine the activity of interest.

- Muscle activation levels and patterns are unique for each user. This means that a learning period must take place before the user can use the exoskeleton.
- Physiological conditions like fatigue and arm posture affect the muscle activation level and pattern. Such factors change throughout the day for each individual, so there is a lot of variability
- Physical electrodes must be placed on the surface of the skin. With sweat and movement, this increases noise to the signal.

CHAPTER 3:

STATEMENT OF PROBLEM AND METHODOLOGY OF SOLUTION

3.1 Statement of Problem

The overall problem of designing and implementing the forearm exoskeleton can be broken down into a few major subcomponents. Firstly, the user input control method must be determined based on available sensor technology and considerations regarding the intuitiveness of various control strategies. Secondly, the mechanical structure must be designed. This is a significant component in the design process, especially because there are limitations regarding available resources and budget. Thirdly, the type of actuator to be used must be decided. This must be selected based on the desired torque outputs, power consumption and most importantly, functionality. Additionally, the safety of the user is a paramount issue. Redundancy and feedback mechanisms must be implemented in the system.

3.2 Methodology of Solution

Most of the challenges in this design project were due to the mechanical structure. In order to keep the project under a limited budget, customized parts could not be used. As a result, it was a challenge to find separate parts that could be integrated together. As well, many parts that are available were not small enough to keep the mechanical structure compact.

While a theoretical design for the mechanical structure was developed, the process of finding and integrating parts required constant revisions of the design. In the end, the design and implementation process involved finding and realizing a workable solution based on the theoretical concept.

CHAPTER 4:

EXPERIMENTATION AND DESIGN PROCEDURE

4.1 Overview

As described in the problem statement in section 3.1, the overall system comprises of a number of blocks as listed in Figure 2.

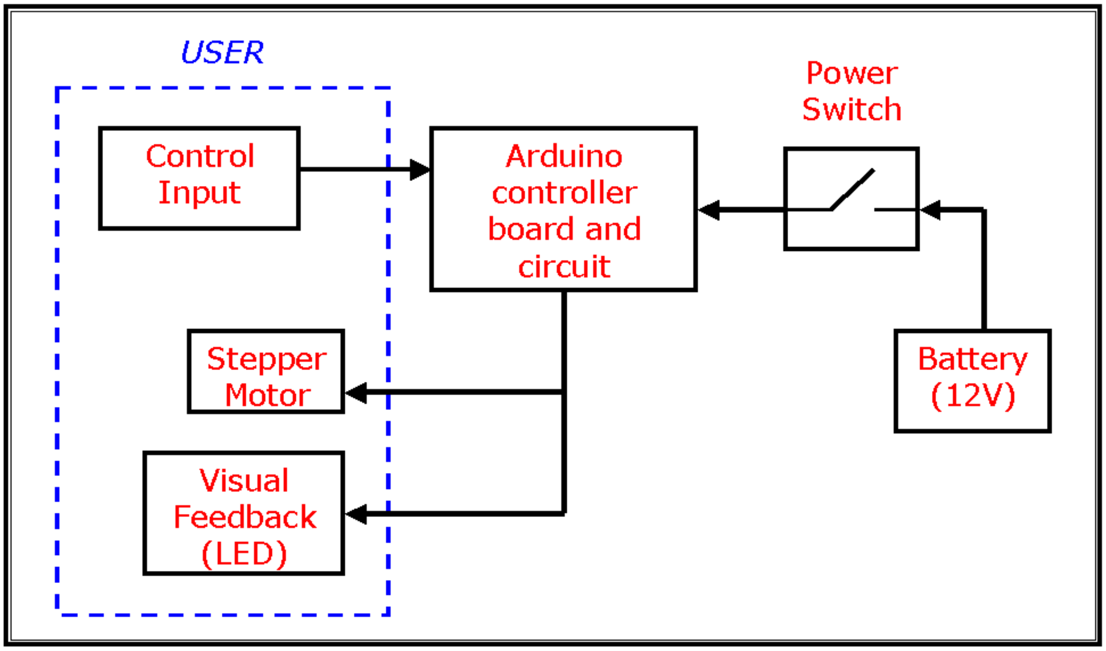


Figure 2 – System schematic block diagram

The control input (switches), actuator (stepper motor) and visual feedback (LED) microcontroller board sends control signals through an H-bridge stepper motor driver, which controls the stepper motor and actuates the exoskeleton. The power switch between the power supply and the rest of the system has a few purposes. First and the most obvious reason, it allows the user to turn the exoskeleton on and off between usage. Second, it allows the user to set the exoskeleton to “idle” such that the user can supinate/pronate freely without power-assistance. Lastly, it acts as a kill-switch in case the user needs to cut power from the system in an emergency.

4.2 User Input Control Method

There were several methods of input control considered in the design process. Two of the main methodologies considered are summarized below.

An EMG-based control methodology was ruled out because of the challenges described in Section 2.3, the complexity of the logic controllers and algorithms to interpret the control signals, and the physical extraction of signals from the user (i.e. using surface electrodes). While many exoskeletons are using this method, it was not reasonable for the goals of this project.

Another method that was initially considered was using QTC (Quantum Tunneling Composite) variable resistance-sensors and FSRs (Force Sensing Resistors), which change its resistances based on pressure or force applied onto them. This would have allowed for some threshold speed control of the exoskeleton, in addition to the directional control. Unfortunately, after preliminary testing, QTCs were ruled out as an option because of its inconsistency and hypersensitivity. Between trials, the same QTCs would produce different results. Between different QTC sensors, the range of resistances for the various forces tested were vastly different. After testing with the FSR sensors, it was ruled out as an option due to the range of forces required to consistently reach certain threshold resistance levels to signal different speeds.

The final input control method selected was to use two push-button sensors, each indicating a corresponding desired direction of rotation. For example, the left switch indicated a counter-clockwise rotation (left hand supination) and the right switch indicated a clockwise roation (left hand pronation). The push-button sensors would be pressed using the thumb of arm wearing the exoskeletong (i.e. the non-dominant hand). A potential implementation is shown in Figure 3. This part would be placed in the glove of the hand exoskeleton.

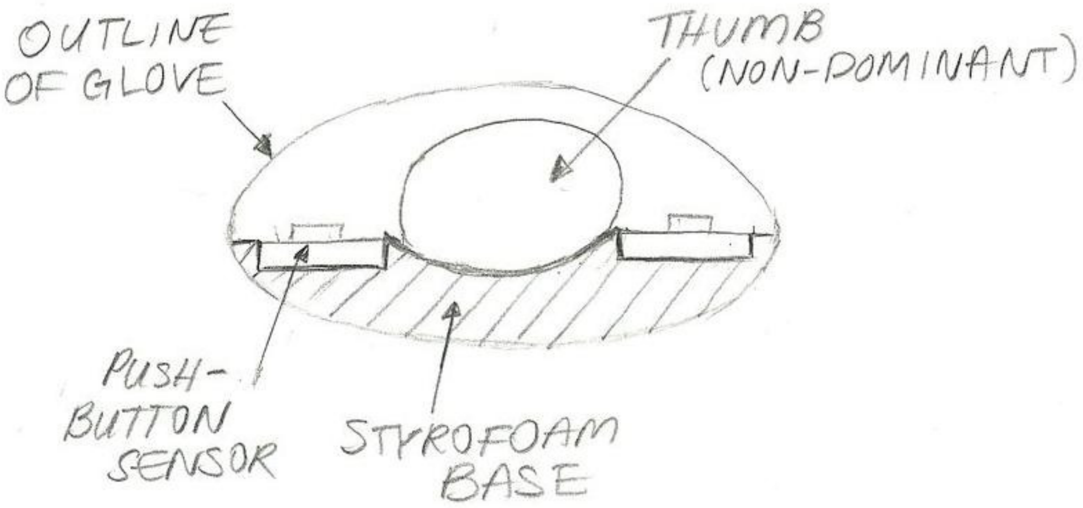
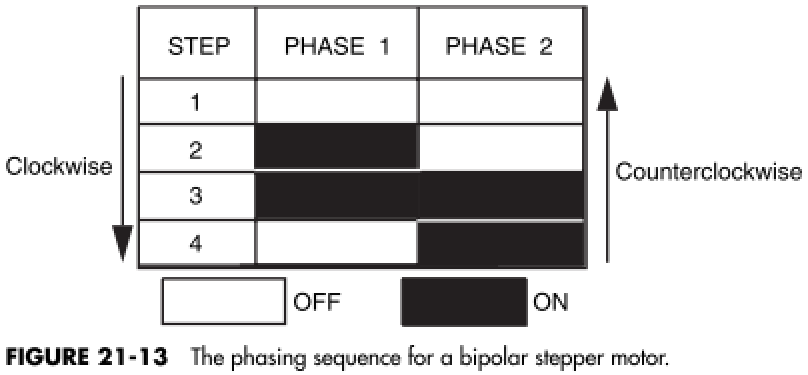


Figure 3 –Input control implementation using push-button sensors

This method was very intuitive for the user to use, guaranteed the user's intentions were properly interpreted, was not prone to triggering false positives, and was inexpensive and readily available. This was a simple and reliable solution to allow the user to fully control the robot at all times.

3.4 Actuation – Stepper Motor

As mentioned previously, one of the goals of the project was for the exoskeleton to be able to hold a desired position for the user. This led to the choice of the stepper motor as the actuator. Stepper motors are controlled by a series of electromagnetic coils, which surround a magnetic central shaft (rotor). Based on which coils have current, the attractive and repulsive magnetic fields cause the rotor to rotate. As a result, following a sequence of the ON/OFF combinations of the electromagnets, the motor can be controlled to rotate continuously. Reversing the order of the sequence results in the motor rotating in the opposite direction. An example of the sequencing is as shown in Figure 4.



STEP	PHASE 1	PHASE 2
1	☐	☐
2	■	☐
3	■	■
4	☐	■

☐ OFF ■ ON

FIGURE 21-13 The phasing sequence for a bipolar stepper motor.

Figure 4[1] *- Phase sequence for bipolar stepper motor*

Specifications

- Type: Bipolar
- Step Angle (degrees): 1.8^o
- Rated Voltage: 12V
- Rated Current: 0.33A
- Holding Torque: 2.3kg*cm

To control the bipolar stepper motor, an H-bridge was used (L293D). The block diagram schematic is shown in Figure 5.

---

[1] McComb and Predko, *Robot Builder's Bonanza, Third Edition* (The McGraw-Hill Companies, 2006), p. 388

BLOCK DIAGRAM

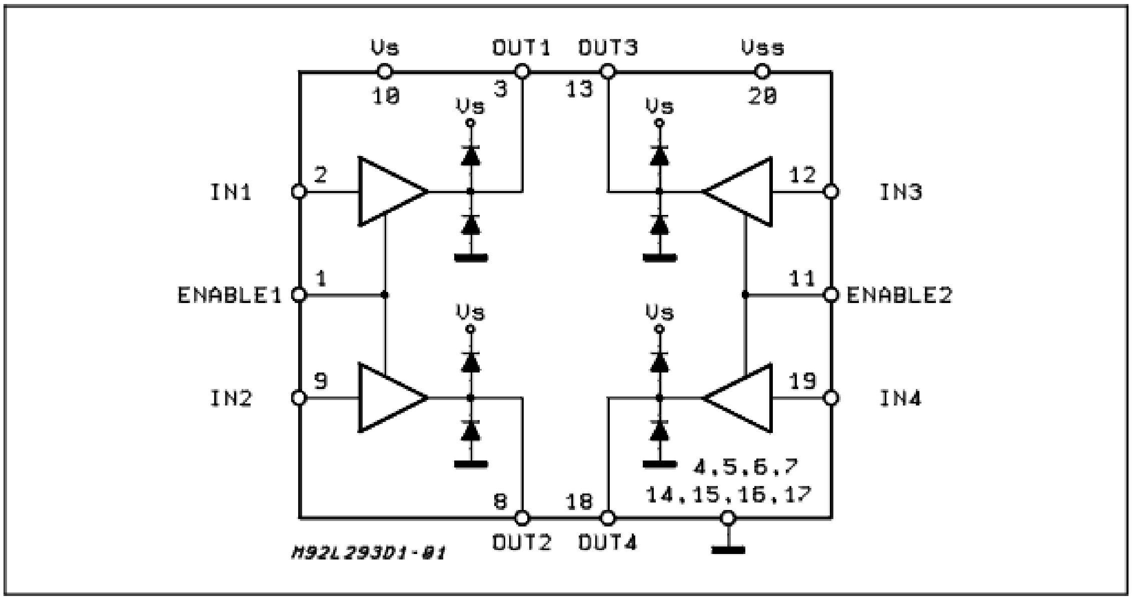


Figure 5[2] - Block diagram of L293D used for stepper motor controller

4.4 Theoretical Design of Mechanical Structure

The theoretical design for the mechanical structure is summarized in Figure 6. The design consisted of a stepper motor, ring gear, torque transmitters, wrist holder and forearm holder. The stepper motor was to be fixed on the user such that it remained stationary. The teeth of gear on the motor shaft needed to match with the teeth of the ring gear. The ring gear was to be worn around the forearm and would be approximately four inches in diameter, depending on the user. This converted the torques of the motor to torques for the exoskeleton and slowed the quick motor speed to a rotational speed that matched the application. Attached to the ring gear, there would need to be some transmitter beams which transferred the torque from the ring gear to the wrist holder. The wrist holder was where the applied

---

[2] http://www.st.com/stonline/books/pdf/docs/1330.pdf

torques would be transferred to the user, thus providing the pronation and supination movement.

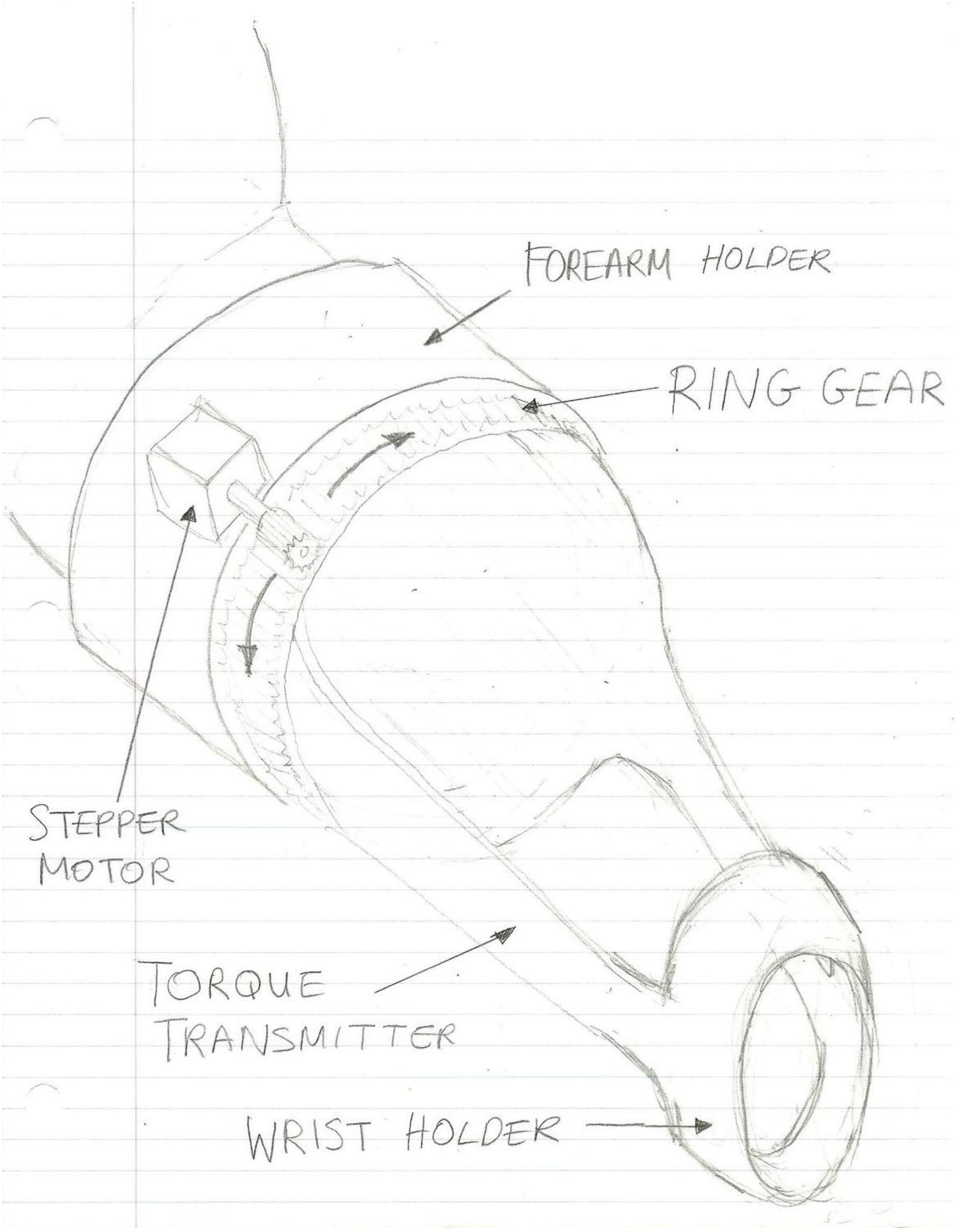


Figure 6 – Theoretical design for mechanical structure

In order for the user to wear the exoskeleton, there had to be at least two layers in the forearm holder. One that rotated (i.e. ring gear) and one that remained stationary on the user's forearm (i.e. forearm cuff). Between these two layers could be a layer of ball bearings, which would create a smooth and frictionless surface for the two ring gear and forearm cuff to slide with respect to each other. The different layers are specified in the Figure 7

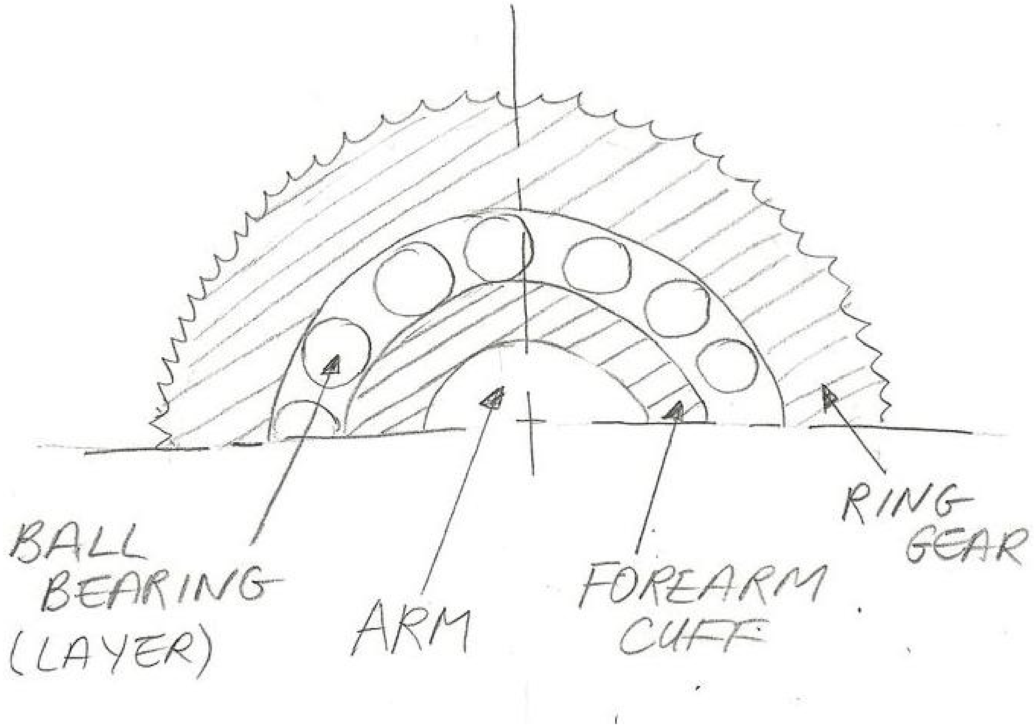


Figure 7 – Cross-section showing layers of forearm holder in theoretical design

4.5 Mechanical Structure

The final mechanical system is depicted in the below image. There are a number of items that complete the mechanical structure, which are described in the following subsections.

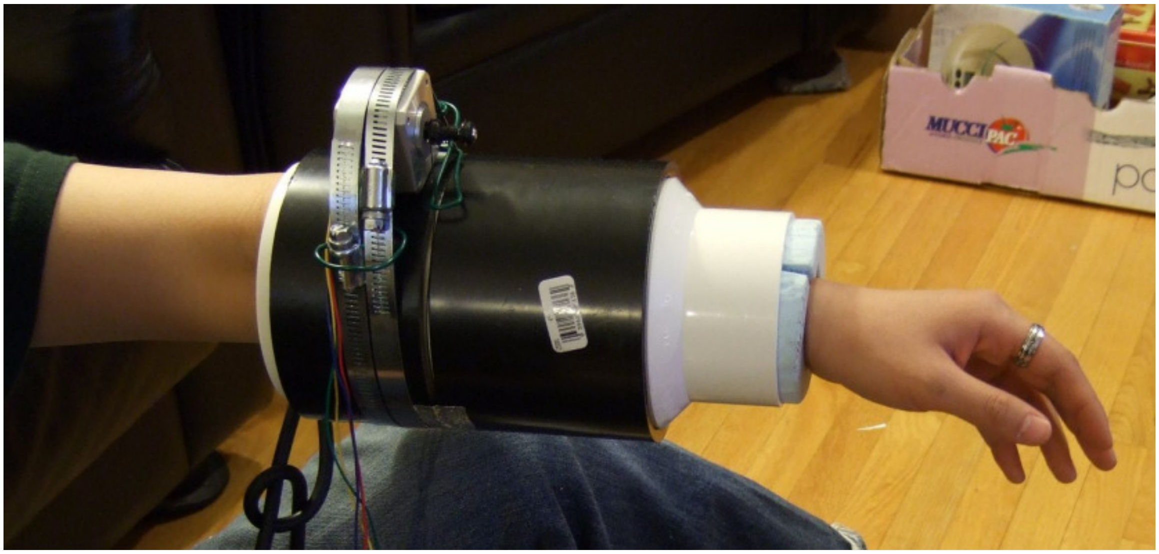


Figure 8 – Photograph of exoskeleton worn by user (final mechanical system)

Overview of Main Structure

The main mechanical structure is composed of two separate units. The first unit is the "stationary unit", which is attached to the forearm and remains fixed. It is attached to the forearm through the use of an air pressure cuff. The second unit is the portion that generates the rotational torques and transfers it to the wrist. The "rotating unit" rotates around the stationary unit, which is realized through the use of a piece of string that is wound through a bidirectional winch. The winch is on the shaft of the motor, which is fixed to the rotating unit. When the motor turns, the string on one side is under tension, which pulls the rotating unit in that direction. This results in a relative rotation with respect to the stationary unit. The rotating unit is attached to the wrist using a custom-shaped Styrofoam cuff. When the rotating unit turns, it pronates or supinates the forearm. The individual components of the mechanical structure are described in further detail in their respective sections below.

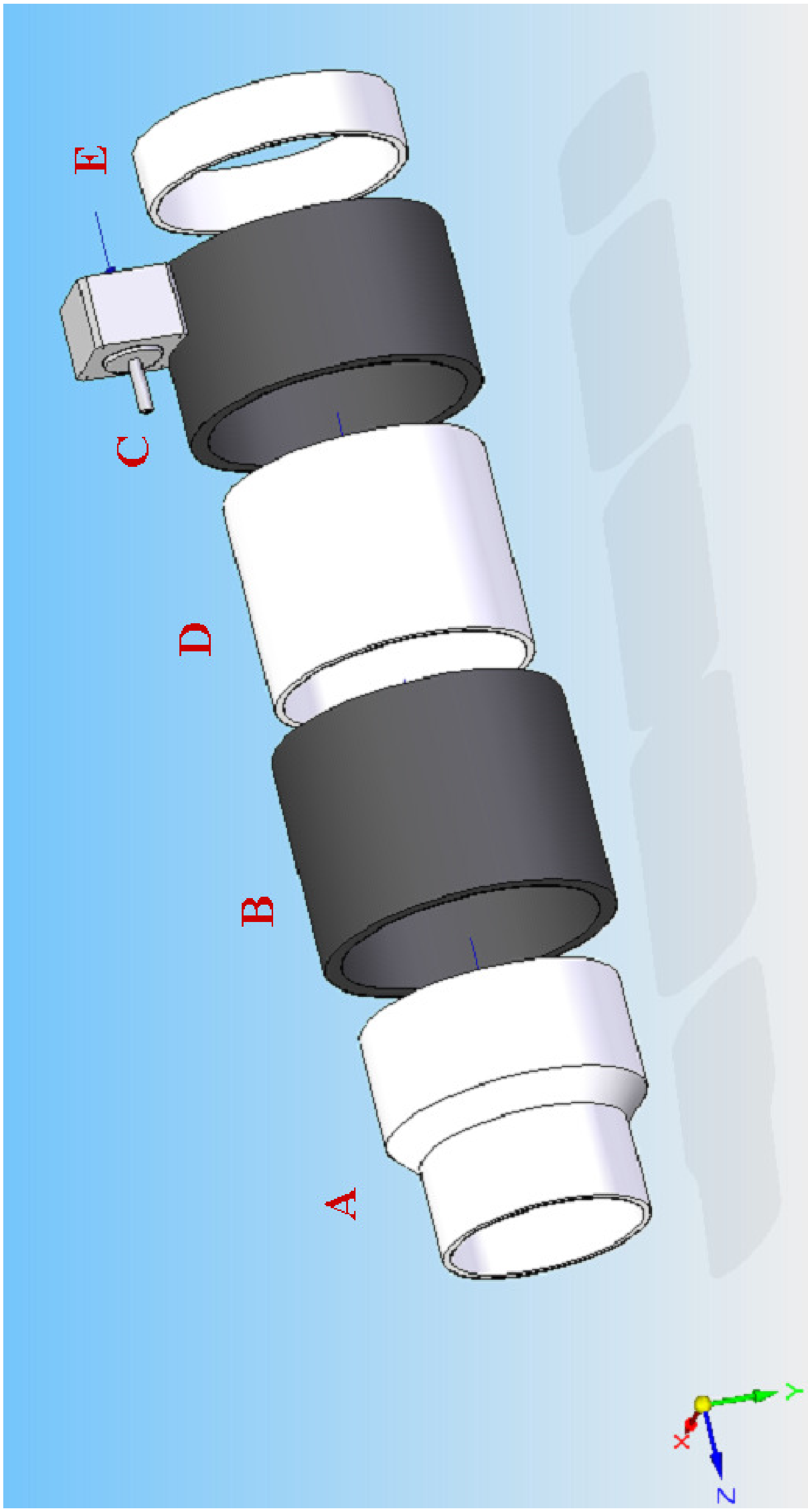


Figure 9 – Exploded assembly view showing all parts of mechanical system

Figure 9 shows the five individual pieces that make up the mechanical structure. Parts D and E are coupled together and act as the stationary unit, which is stabilized on the forearm as described previously. Parts A, B and C are coupled together and act as one rotating unit. The stepper motor is attached to part C using two hose clamps. When the motor turns with respect to the stationary unit, Part C and the rest of the rotating unit turns as well.

Note that the labels (i.e “Part A”) used in the diagram for each part will be used throughout the remainder of the report.

Dimensions

The diameter of the pipes are quite appropriate for the forearm, ranging from 4-5 inches, which gives enough room for a forearm cuff between the user and the exoskeleton. The selection of the pipe diameter size is a trade-off between bulkiness and torque output. While selecting pipes with smaller diameters would decrease the size of the structure, the torque generated by the system would decrease due to gear reduction principles. This will be discussed in more detail in Section 4.7.

Parts selection – PVC and ABS Coupling Hubs

Each unit is composed of individual parts, three for the rotating unit and two for the stationary unit, which are different PVC (white plastic) and ABS (black plastic) coupling hubs. The first and most obvious characteristic to consider about these parts was that they were cylindrical. While looking for parts, one major challenge was to find was a ring gear that was of appropriate size and weight that could be worn on the forearm. Additionally, the gears would have to be integrated with the gears from the motor somehow to transmit the rotation from the motor to the structure. Then, the ring gear would need to be attached to a physical structure to connect to the wrist in order for the torques to transfer. Using the two types of pipes together replaced most of these components, which made it a simple and effective implementation.

The most advantageous aspect of the PVC and ABS, in addition to the simplifications it provides as described previously, was the way the parts fit into each other. The ABS parts fit into the ABS parts for the same given diameter (i.e. four inches) with a perfectly sized gap, which was important for frictionless movement while maintaining a secure fit, staying solid and rigid as a structure. Realistically, there is friction between the surfaces, but the material and the gap seemed to allow the parts to spin sufficiently smoothly. Without any load, the ABS piece would continue spinning after an initial rotation with respect to the PVC piece. Even while applying pressure to the joint to increase friction between the two surfaces, the parts were still able to spin smoothly. Additionally, it was considered that the surfaces could be smoothed or lubricated if required, although lubrication was not a very appealing choice since it would be messy and also attracts dirt and become less effective over time. Using the ABS and PVS piping was a simple realization of the turning mechanism that was theoretically designed. The smooth spinning replaced the need for the ball bearings, which would have been very heavy, expensive and difficult to implement. These were the primary considerations to select the PVC-ABS combination as a workable solution for the mechanical structure.

The Stationary Unit (S.U.)

The stationary unit is the point of contact at which the physical structure of the exoskeleton is attached and stabilized on the user's forearm. In order to generate a rotation around the forearm, there must be a part of the physical structure that is fixed to the forearm. This is the function of the stationary unit. Figure 10 shows the two pieces, Part D and E, that make up the stationary unit in the mechanical structure. The stationary unit is attached to the user's forearm using a cuff, which is realized using an air pressure cuff.

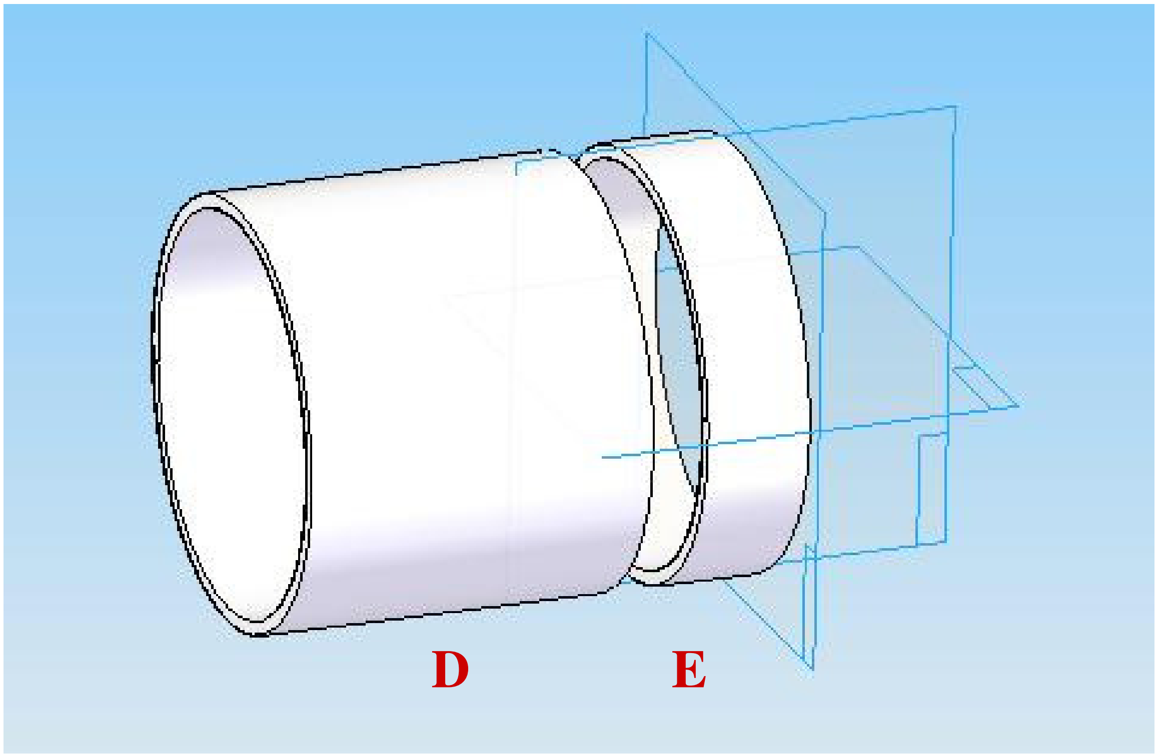


Figure 10 – The parts of the Stationary Unit

Forearm Air Pressure Cuff

Ideally, the stationary unit would be permanently attached to a cuff, which would be custom-fit to the user's forearm. The cuff would need to be comfortable yet tight enough such that the motion of the rotating unit would not cause the cuff (and the entire physical structure) to slip on the forearm. A temporary solution to such a customized cuff was an air pressure cuff as shown in Figure 11.

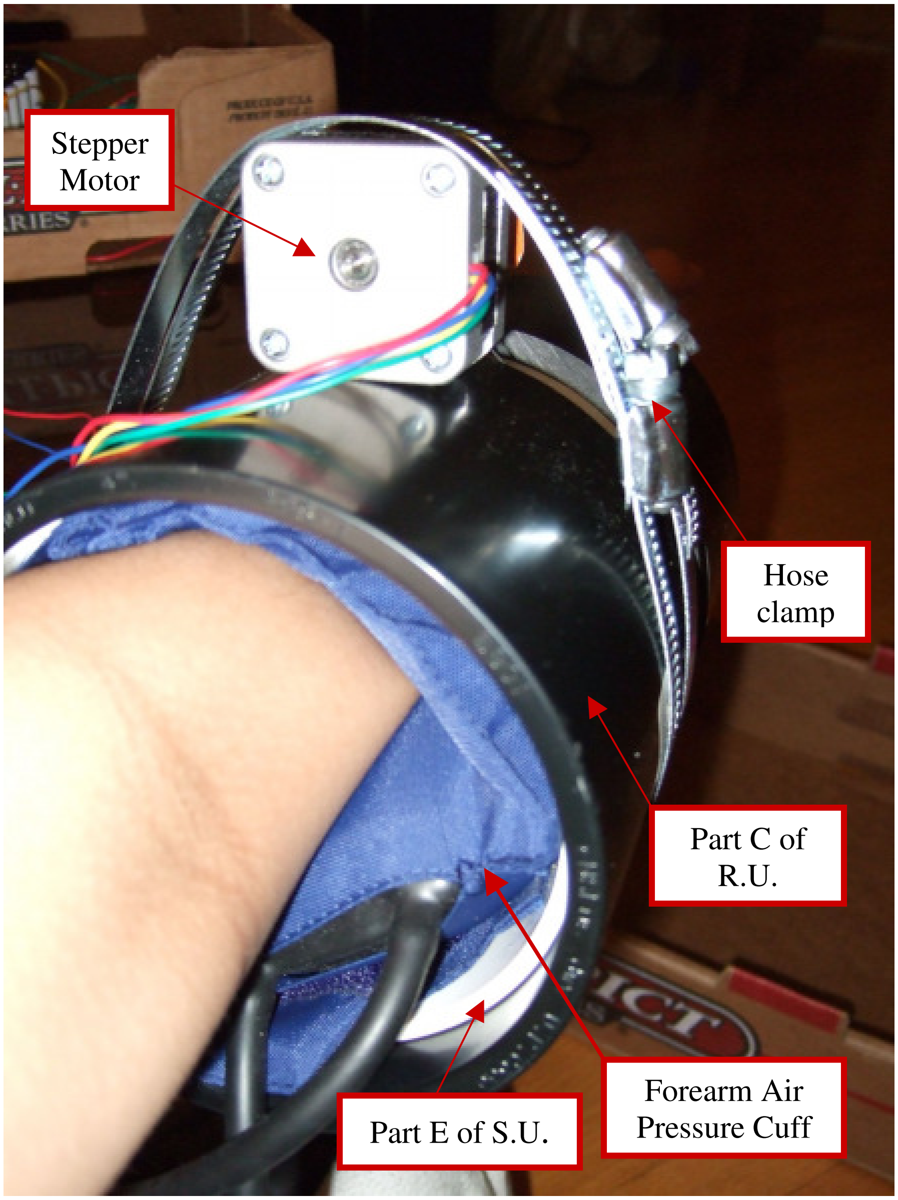


Figure 11 – Photograph of exoskeleton (forearm end)

The air pressure cuff was selected because it could conform to the user's forearm, which was not perfectly cylindrical. The air pressure cuff was placed within the two pieces of the stationary unit. With the user's forearm positioned inside, as air was being pumped into the cuff, the forearm was secured to the physical structure. The pressure from the cuff needed to sufficiently hold the exoskeleton to the user's forearm without slipping when the motors were actuated.

The amount of pressure used was kept to the minimum level to obtain the necessary force in order to minimize the amount of obstruction to blood circulation, which would result in discomfort for the patient and safety concerns. In addition to these concerns, there was another reason for keeping the pressure low. With greater pressure in the cuff, there was more pressure holding the stationary unit to the rotating unit. Specifically, the friction between Part D and E with Part C was greater, reducing the efficiency of the torque transmission.

The Rotating Unit (R.U.)

The rotating unit is the portion of the exoskeleton that transfers the torque from the motor to the user. Ideally, based on the theoretical design, the motor would be attached to a fixed part of the exoskeleton, which would turn the ring gear, directly transferring the torque of the motor to the user. However, with this implementation, the motor was actually attached to the rotating unit. In other words, instead of holding the bulk of the motor stationary and allowing the shaft to rotate, the shaft can be viewed as the stationary part, with the rest of the motor rotating around the shaft. Since the motor is attached to Part C of the rotating unit, when the motor turns with respect to the shaft, the bidirectional winch system allows the entire rotating unit to turn. The bidirectional winch, which is attached to the motor shaft, is described in detail in Section 4.6

As depicted in Figure 12, the rotating unit consists of Part A, Part B and Part C. Part A fitted into Part B and was secured using a strip of aluminum tape. Part B and Part C were attached using a strip of aluminum tape as well. There was an intentional and necessary gap between the parts, which was to allow room for the string in the winch system. Careful attention was required to ensure the tape did not interfere with the string. Besides connecting the two parts together physically, the tape had a significant role in the transfer of torque. A longer strip was used to hold the two pieces together to decrease the amount of shear between the two parts from relative rotations. When Part C rotated due to the motor, if the attachment between Part B and C was not sufficiently rigid, the torque would not be effectively transferred to Part C. As well, the shear stress was higher for a larger gap between Part B and Part C, so it was kept to a minimum.

Aluminum tape was used because of its strength and rigidity relative to other tapes. While permanent adhesives or other attachments could have been used, the aluminum tape was easily removed and replaced. This was important through the testing process for calibration and also transportation of the exoskeleton during construction.

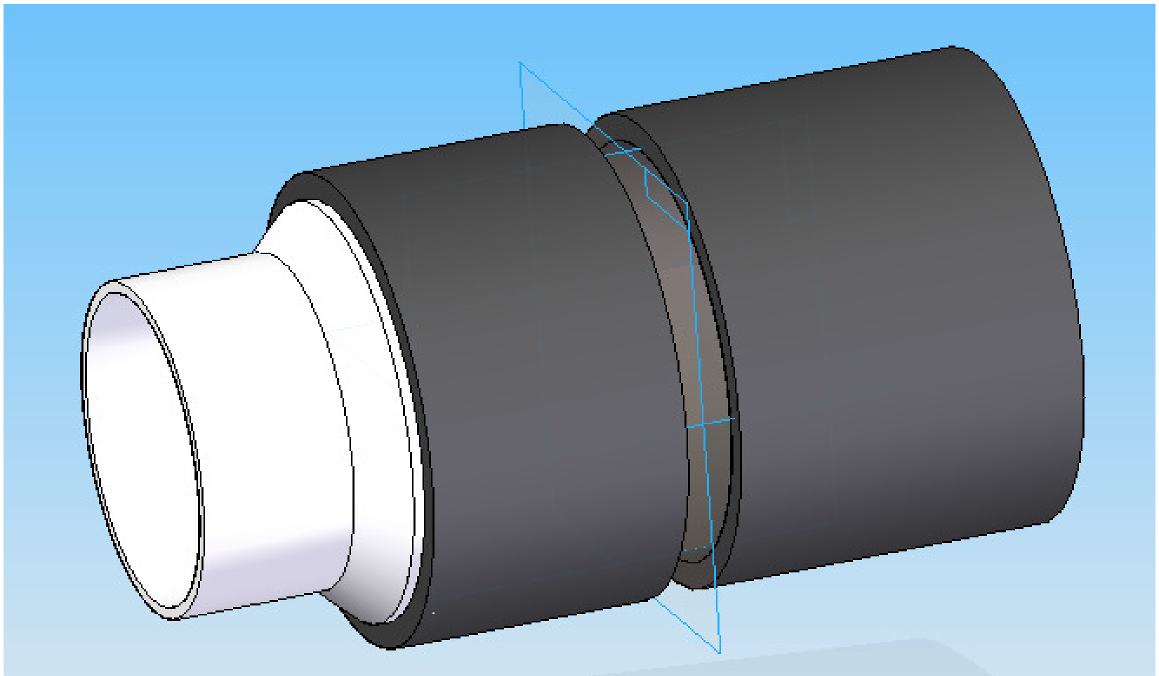


Figure 12 –The parts of the Rotating Unit

The torque that was transferred from Part C to Part A and B was transferred to the user using a wrist cuff. Similar to the requirements of the forearm cuff, the wrist cuff needed to be comfortable for the user to wear and effective in keeping Part A fixed to the wrist such that there was loss in the torque transfer. It is through the wrist cuff that the mechanical system is able to pronate and supinate the user’s forearm. The solution for this wrist cuff was to use Styrofoam.

Styrofoam Wrist Cuff

A cylindrical piece of Styrofoam that fitted snugly into Part A was cut in half. Each half was carved to fit the top and bottom halves of the user's wrist. Styrofoam was selected because it was easily carved or shaped, cheap and readily available and stiff enough to avoid any noticeable shearing between the wrist and Part A during relative rotations. The cuff fitted into Part A as shown in Figure 13.

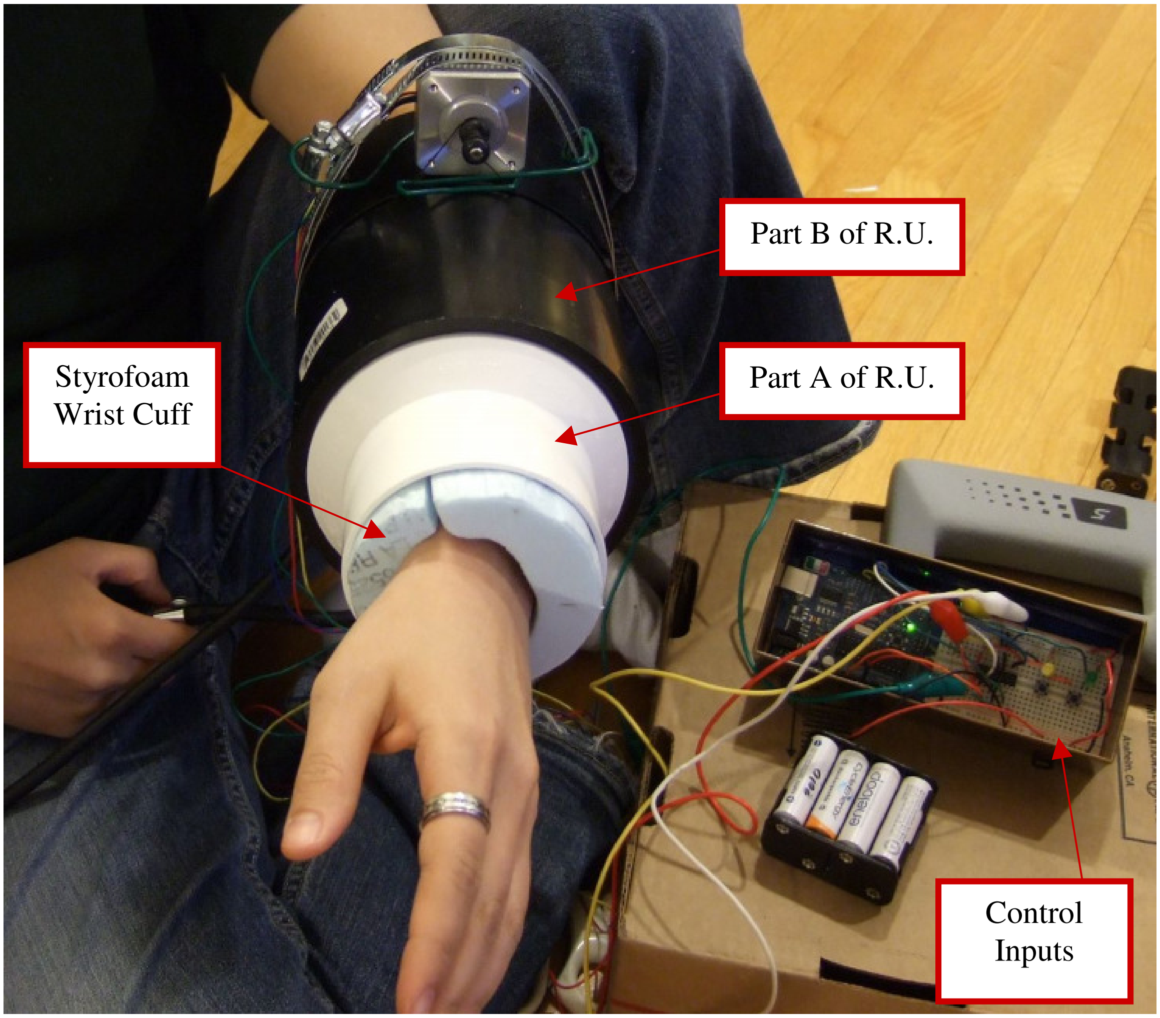


Figure 13 – Photograph of exoskeleton (wrist end)

4.6 Power Transfer Mechanism: Bidirectional Winch Design

In order to turn the rotating unit from the stepper motor, a bidirectional winch system for the motor shaft was used, as shown in Figure 14.

The string is wound in one direction (i.e. clockwise) within section F of the winch. In section G, the string is wound in the opposite direction (i.e. counter-clockwise). Depending on the direction, the rotating unit is turned by the tension of the string from one of the sections pulling on part D as the motor shaft rotates. At the same time, the string in the other section releases. Ideally, there would be no losses while both strings remain taut the entire time. The strings are attached at the bottom of Part D by drilling a set of holes to allow for a knot. The rubber stoppers at the end of each section act as boundaries for the string. The string being used is braided tip-up fishing line. It was selected because it was rated for 20 pounds of load, which should be sufficient for the amount of torque being generated by the system.

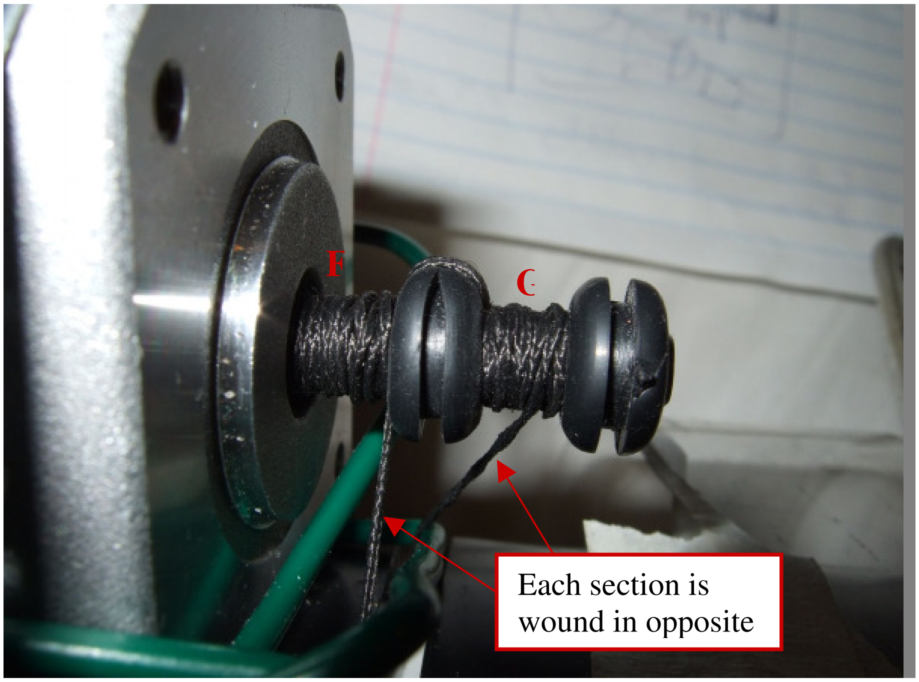


Figure 14 – Photograph showing bidirectional winch system on motor shaft

From the sketch below (Figure 15), it is clear that when the motor shaft rotates in a counter-clockwise direction, one string is pulled while the other is being released. The former remains in-tension, which is pulling the structure to rotate in a counter-clockwise direction as well. If the motor shaft turned in the other direction, the opposite would occur. The strings are attached to the bottom of the structure such that there is enough string for the motor to travel the necessary range of angles (around 120^o in practice).

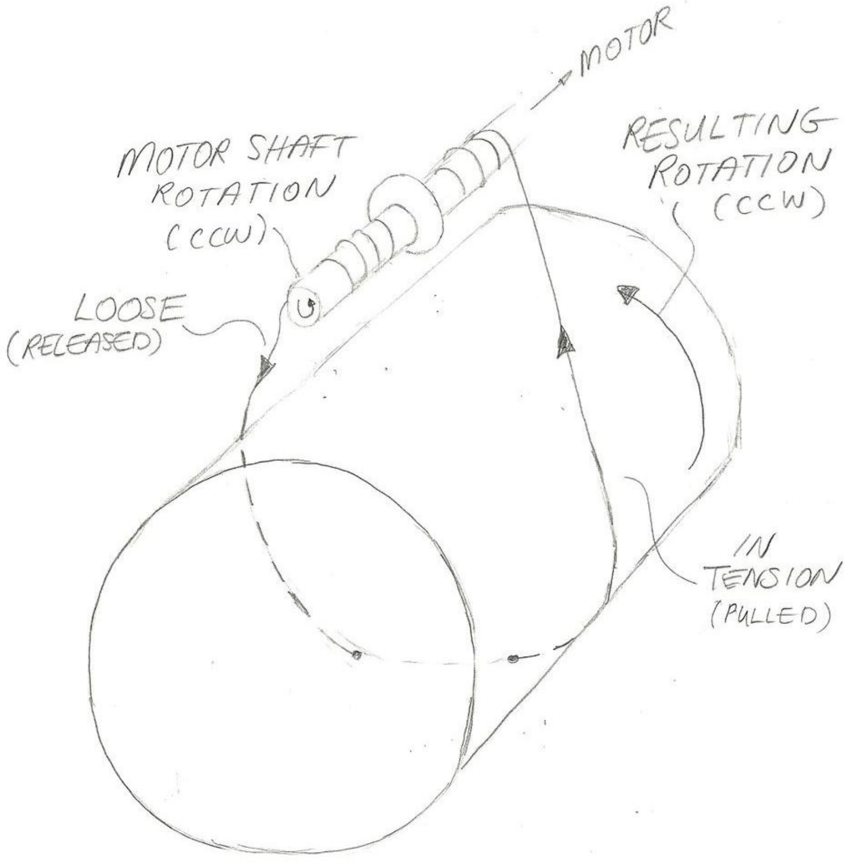


Figure 15 – Sketch explaining bidirectional winch system

4.7 Torque Considerations

Gear Reduction

The concept of gear reduction is demonstrated in Figure 16.

$\tau = r \times F$ (refer to Section 5.2 for more details)

Since the gears are connected to each other, they share the same force. However, since each gear has a different r (radius, number of teeth around the circumference, or some ratio relating to the size), the amount of torque is proportionally different. This concept can also be applied to output speeds.

Applying this concept to the mechanical structure, it was estimated that the system should be able to amplify the motor torque 22 times. This was assuming the radius of the motor was 2.5 mm and radius of the forearm structure was 57 mm.

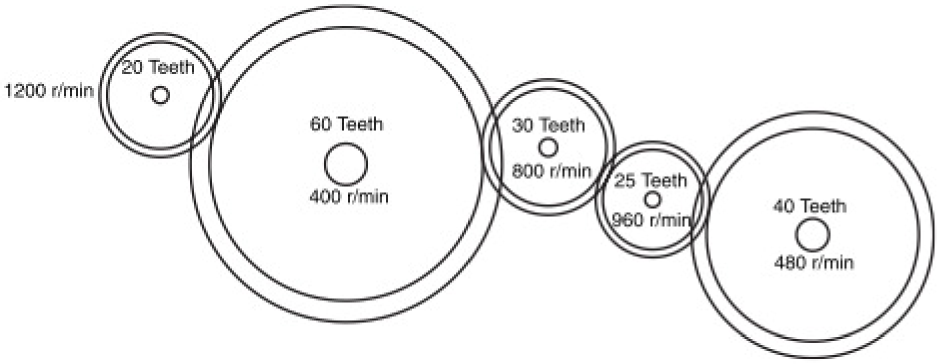


FIGURE 19-7 Gears driven by the 20-tooth gear on the left rotate at different speeds, depending on their diameter.

Figure 16[1] *- Effect of gear reduction on rotation speed based on diameter*

4.8 Power Considerations

When selecting the power source, it is obvious that DC batteries are required for portability. Eight AA batteries were chosen because of they are very common in the household. Specifically, rechargeable batteries are more suitable for this application (to drive the motor) than alkaline since the former have much higher current draw due to the low internal resistance compared to the latter.

Based on rechargeable AA batteries and the maximum current draw rating of the stepper motor, the user should be able to use the robot for six hours before needing to recharge. Since the robot would not be turned on for the entire day, and would not be running at the maximum current draw at all times, this seems reasonable for daily usage.

---

[1] McComb and Predko, *Robot Builder's Bonanza, Third Edition* (The McGraw-Hill Companies, 2006), p. 334

4.9 Safety Considerations

The control mechanism was chosen with safety in mind. Since the user has complete control over the exoskeleton's actuation at all times, the system should be quite safe. It is expected that the user would control the exoskeleton to actuate within a comfortable range of motion. To stop the exoskeleton from continuing its motion, the user simply needs to stop holding down the switch. However, in case the input controls are pressed accidentally or the user is unable to let go of the switch, there are a few safety mechanisms implemented.

To confirm the user input was received by the system and that the exoskeleton is actuating, LEDs are used as visual feedback to the user. If the input controls were pressed without the user's awareness, the LEDs indicate to the user that the robot has received a signal to actuate. It should be noted that if both switches were pressed simultaneously, the microcontroller would not actuate the motor.

The length of the string could easily be shortened to limit the possible range of motion to ensure the user would not actuate the robot to an angle that would cause harm. In the current exoskeleton, the string was kept to the maximum length for testing purposes. Physical stoppers could be added to the mechanical structure for the same reasons, but again, this has been omitted from the current robot for testing purposes.

CHAPTER 5:

TESTING – RESULTS AND DISCUSSION

5.1 Problems Encountered

The initial testing setup was to apply a load (using weights) at Part A, which was to simulate a torque applied at the wrist. This was the closest location to choose in order to simulate the torques a user would experience wearing the wrist cuff. This setup is shown in Figure 17.

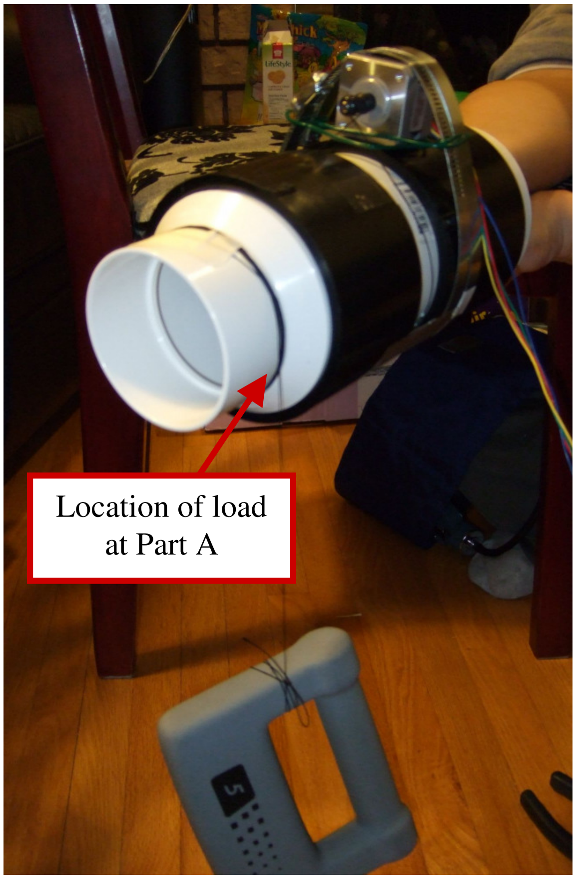


Figure 17 – Photograph showing initial testing setup

The results from the testing performed using this setup seemed inconsistent and incorrect. The loads the system was able to withstand exceeded any of the torques we were able to apply on the robot. It was deduced that the loads being applied onto the system were not transferring to the motor (which would be required to test the motor's output torques). There were two sources of error that were identified. Firstly, the string attaching the load to Part A was wrapped a number of times to help increase friction. However, instead of rotating Part A and the entire rotating unit, the load seemed to simply tighten the wrappings. Secondly, a cantilever effect was present between Part B and A. Instead of the load turning the entire rotating unit, it seemed to pull Part A down while the remaining unit was kept parallel to the ground. This effect is described in more detail below.

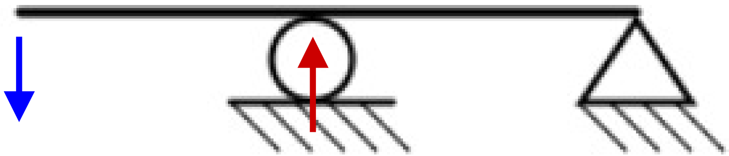


Figure 18[1]– Example of a simple cantilever beam

Figure 18 is an example of a simple cantilever beam, which is supported at one end and another between the load and the end support. The forces and reaction moments due to the structure are shown, with the blue arrows indicating the load forces and the red showing the reaction force required to keep system in equilibrium.

Figure 19 shows how Part A and B acted as a cantilever beam when a load is applied at point X, which is the tip of Part A as indicated in the diagram. Due to the load, a moment was created at point Y, which resulted in a force at point Z since the structure is rigid. It was the force at Z that created more friction which acted against the rotation of Part A relative to Part B.

---

[1] http://en.wikipedia.org/wiki/Cantilever#cite_note-0

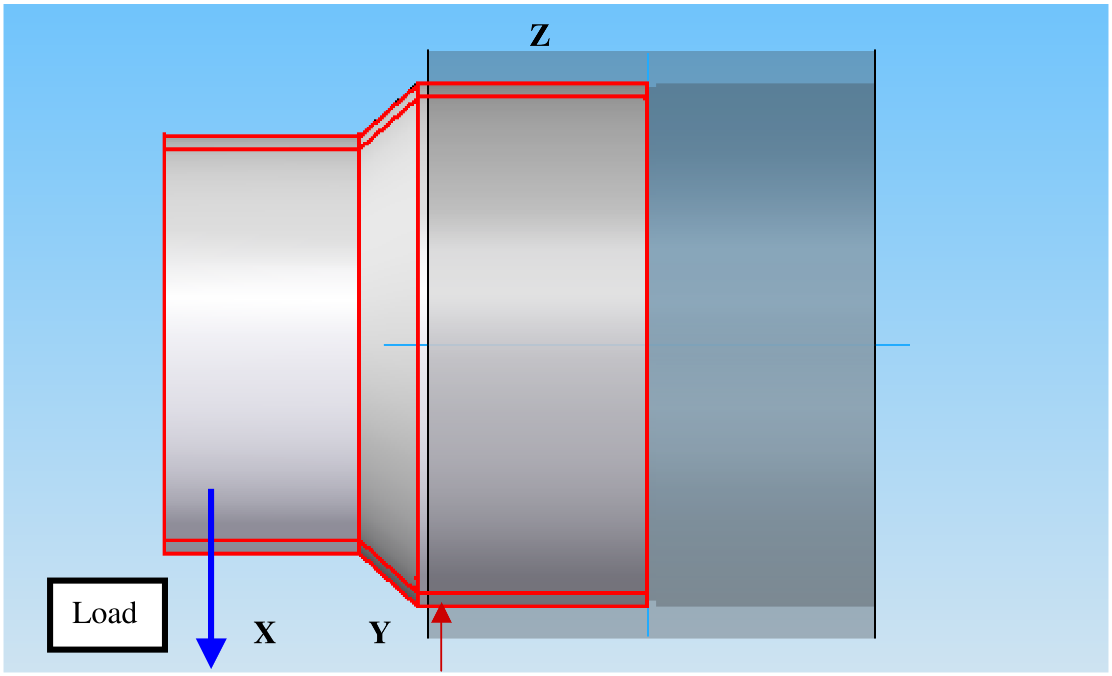


Figure 19 – Cantilever effect on exoskeleton between Part A and Part B

A reaction couple acting at point Y and Z is required to resist the inner collar in equilibrium. These reactions are the forces applied between the surfaces of the collar. Since the frictional force between the surfaces is equal to the normal force times the coefficient of friction, the main resistance of the collar to rotate is proportional to the applied load.

This is described in the following equation:

$$F=U*P\{2(XZ)/(YZ)-1\}$$

where

F is the additional load

P is the load

(XZ) is the distance between X and Z

(YZ) is the distance between Y and Z

U is the coefficient of friction

Note that for the exoskeleton, F is the tension in the string in addition to the applied torque to the wrist.

5.2 Final Testing Setup

In order to address the two problems described in Section 5.1, which were causing inconsistent and inconclusive results, a few changes were made to reach the final testing setup as depicted in Figure 20. Instead of using string to attach the load, a plastic belt (may not be visible in the image) was used, which was adhered to the structure using tape.

As well, the load application location was moved from Part A to Part B. By moving the load location to point Z from Figure 19 in section 5.1, the cantilever effect was removed since the torque was now applied directly to Part B. However, one drawback was that the torque measurements using this setup would not truly represent the torques the exoskeleton was capable of generating since the gear reduction discussed in Section 4.7 was now excluded, which would have increased the effective torque at the wrist. As a result, the values from the following tests were underestimations of the performance of the system.

The loads were applied and measured using a stain gauge, which was attached to a plastic belt that was wrapped around Part B as shown in Figure 20. A strain gauge was chosen for the tests because it was easy to use with this setup and the maximum load achieved was recorded.

Note that all of the tests (except one) were executed using a battery pack with a voltage between 10-10.2 V. At full capacity, the battery pack should have a voltage of 12V. As a result, the torque measurements were slightly lower than what the exoskeleton could potentially output as a maximum.

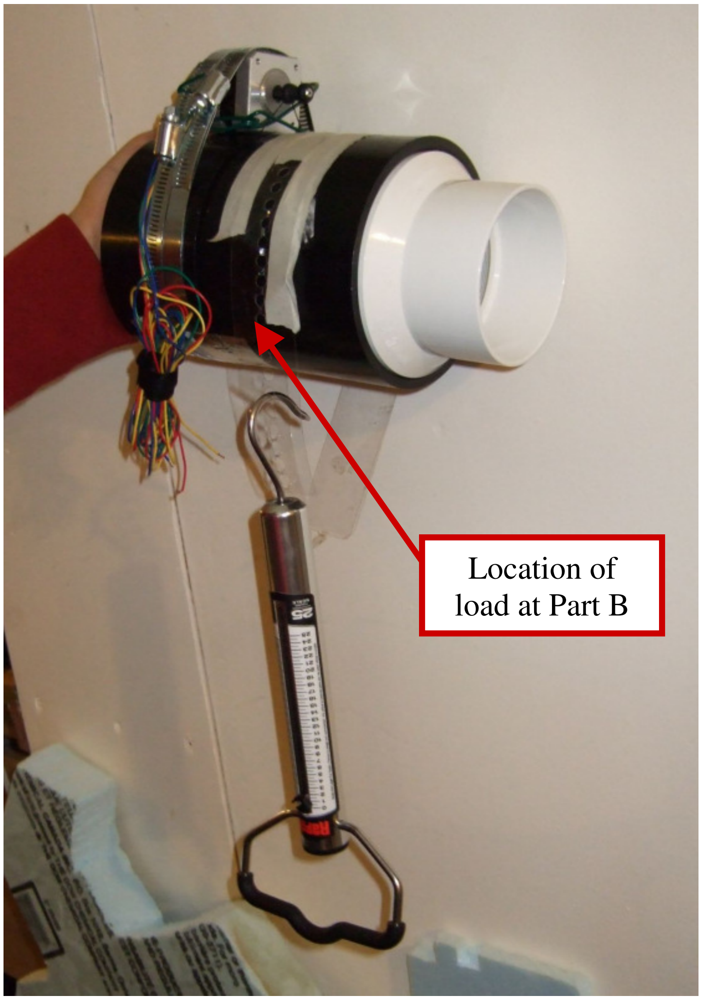


Figure 20 – Photograph showing final testing setup

Torque Conversion

The loads measurements were converted into torque values using the following relationship:

$$\tau = r \times F \text{ or } \tau = rF\sin\theta$$

where

τ is the torque vector

r is the displacement vector corresponding to the lever arm

F is the force vector

θ is the angle between the force vector and lever arm vector

With this structure and setup, θ was always 90° since the applied load was tangential to the circular surface and imaginary lever arm. As a result, magnitude of the torque was simply the lever arm length multiplied with force. For these tests, the length of the lever arm was the radius of Part B (6.4 cm) and the force was the load for each trial.

5.3 Running Torque Testing

Running torque, or pull-out torque, is the torque a stepper motor can sustain while rotating without slipping.[2] "Mostmotors are rated by their running torque, or the force they exert as long as the shaft continues to rotate. For robotic applications, it's the most important rating because it determines how large the load can be and still guarantee that the motor turns."[3]

To test running torque, an input was sent to the exoskeleton to rotate while the strain gauge was held stationary. As the motor rotated the exoskeleton in one direction, the strain gauge applied a resistive force in the opposite direction. The input was held until the motor slipped, indicating that the maximum running torque was reached. Since running torque is affected by speed[2], several tests were executed using different motor speeds.

Trial	Load (lbs)	Torque (Nm)
1	2	10.08
2	2	10.08
3	1.6	8.06
4	2	10.08
5	1.5	7.56

Table 1: Test I – Running Torque test at 45 rpm (with Vs = 12.8V)

---

[2] http://www.aeroflex.com/ams/motion/datasheets/stepper_info_document.pdf

[3] McComb and Predko, *Robot Builder's Bonanza, Third Edition* (The McGraw-Hill Companies, 2006), p. 379

Trial	**Load (lbs)**	**Torque (Nm)**
1	1.5	7.56
2	1.4	7.06
3	1.5	7.56
4	2	10.08
5	1.5	7.56

Table 2: Test II – Running Torque test at 45 rpm (with Vs = 10-10.2V)

Trial	**Load (lbs)**	**Torque (Nm)**
1	1.5	7.56
2	1.5	7.56
3	1.8	9.07
4	1.5	7.56
5	1.3	6.55

Table 3: Test III – Running Torque test at 50 rpm (with Vs = 10-10.2V)

Trial	**Load (lbs)**	**Torque (Nm)**
1	1.5	7.56
2	1	5.04
3	1	5.04
4	1.2	6.05
5	0.5	2.52

Table 4: Test IV – Running Torque test at 60 rpm (with Vs = 10-10.2V)

5.4 Holding Torque Testing

Holding torque is the amount of torque that can be applied to a stepper motor shaft without causing it to rotate. This is measured when the stepper motor is powered.

To test holding torque, the exoskeleton was powered and held stationary (being careful not to touch the rotating unit which would add friction). No inputs were pressed since this was to test the exoskeleton's ability to hold its position. The strain gauge was used to apply and measure the torque being applied to turn the exoskeleton. Similar to the Running Torque tests, the holding torque would be the maximum load recorded on the strain gauge, which corresponded to the torque required to turn the motor shaft while it was powered.

Trial	Load (lbs)	Torque (Nm)
1	>11	>55.44
2	>11	>55.44
3	>12	>60.48
4	>10.5	>52.92
5	>11	>55.44

Table 5: Test V – Holding Torque test (with Vs = 10-10.2V)

5.5 Detent Torque Testing

Detent torque is the holding torque of a stepper motor when it is de-energized or not powered. It is the minimum torque of a stepper motor, typically being 1% of the holding torque. [4]

The detent torque of the system was measured using the same testing procedure as the Test V, the Holding Torque tests. The only difference was that the power switch was turned off, such that the exoskeleton was in "idle" mode.

---

[4] http://www.micromech.co.uk/dir_terms/detent_torque.shtml

Trial	Load (lbs)	Torque (Nm)
1	6	30.24
2	6	30.24
3	7	35.28
4	7	35.28
5	6	30.24

Table 6: Test VI – Detent Torque test (with Vs = 0V)

5.6 Discussion

Running Torque Tests (Tests I to IV):

Test	Voltage Supply (V)	Motor Speed (rpm)	Average Load (lbs)	Average Torque (Nm)
I	12.8	45	1.82	9.17
II	10-10.2	45	1.58	7.96
III	10-10.2	50	1.52	7.66
IV	10-10.2	60	1.04	5.24

Table 7: Summary of Average Running Torques (over five trials each)

From Table 7, it is evident that there is a trade-off between running torque and motor speed. As the motor speed increased, the running torque of the system decreased. Since the exoskeleton was intended to supinate or pronate the user's forearm at a slow to moderate speed, using a lower motor speed is very reasonable to gain higher running torque. As well, when tested with a voltage supply of 12.8V (using a fresh set of Alkaline batteries) instead of the 10-10.2V used throughout the experiments, the running torque was substantially higher as demonstrated in Test I and Test II using 45 rpm.

While the running torques were not very high, they were sufficient to demonstrate the concept for the purposes of this project. When the exoskeleton was worn, it was able to supinate and pronate the user's forearm without slipping at 45-50 rpm. Assuming 0^o is at the top of the forearm, the system was able to continue powering the rotation even after the motor position exceed +/- 90^o , with the weight of the motor added to the load, without slipping.

Holding Torque Test (Test V):

For this test, loads of 11-12 lbs were not sufficient to rotate the motor shaft. We were unable to apply loads greater than the ones specified for each trial while holding the exoskeleton stationary. As a result, the actual holding torque of the system could not be quantified.

Although an exact holding torque was not measured, the test shows that the system was able to achieve a very high holding torque, far exceeding the minimum expectations when initially designed. Using the average maximum pronation/supination torques of 13.1-16.2 Nm as a reference, the measured torques were far greater than what was needed for typical daily activities.

Detent Torque Test (Test VI):

The detent torque was measured to determine the amount of resistance the user would feel when rotating with the exoskeleton powered off. Unfortunately, this would be a major problem for the user since the exoskeleton should minimize the amount of resistance to the user's self-generated rotations when in "idle" mode (i.e. powered off).

Measuring the detent torques was also useful as a point of reference for the holding torque of the system especially because actual values could not be quantified. One explanation for the extremely high holding torque could be that the system itself has a lot of resistance. Since the system provides such high detent torque, it can be estimated that potentially half of the holding torque was not due to the motor; rather, the system itself was adding to it.

General Discussion:

In addition to the quantitative tests described in this chapter, the exoskeleton was worn and tested for qualitative tests to determine its general usability, functionality, comfort, and safety.

The exoskeleton was able to successfully pronate and supinate the user's forearm without any exertion of energy from the user. The system was safe to use as the controls were very intuitive and reliable, giving the user full control over the exoskeleton at all times. Considering the user would wear the exoskeleton throughout the day, the entire structure was quite heavy (just over 1 kg). However, the materials used for the physical structure were selected because of their availability, cost, and ability to be integrated with each other. As a result, the weight was not a primary concern and was not expected to be lightweight.

As mentioned in the previous discussions, there were several areas of difficulty encountered through the testing process, which were most likely due to torque transmission loss and some assumptions made regarding the biomechanics of the forearm. From testing, there were a number of potentially problematic areas that were identified. The following includes some factors that were expected to be sources of problems:

Anatomical/Biomechanical factors:

- The simplification for modeling pronation/supination motion as perfectly axial resulted in torque transmission problems. Instead of rotating the forearm in a natural movement, there was some added resistance at some points of the rotation. This could be a source of discomfort and potential safety concern. As well, due the approximation, it was very difficult for the user to rotate the forearm when the exoskeleton was off. This was because the user's movement was not perfectly aligned with the structure's axis of rotation. This is a source of limitation in the user's ability to move without power-assistance.
- Muscles on the forearm tended to rotated around the ulna and radius (forearm bones) instead of remaining stationary. As a result, even though the stationary

unit remained fixed to the forearm relatively, the stationary unit could actually rotate

Mechanical factors:

- Friction between any parts within the stationary and rotating units were a source of torque loss
- The air pressure cuff resulted in two areas of concern. Over time, the forearm would probably be uncomfortable to use due to the pressure, cutting off circulation to and from the hand. As well, the pressure pushed the stationary unit against the rotating unit, which probably resulted in additional frictional forces between the parts. The amount of pressure used could be varied, but a minimum pressure is required to keep the stationary unit fixed to the forearm.
- The Styrofoam wrist cuff was uncomfortable to wear over time since the shape of the cuff was only approximately carved to fit the user’s wrist. Ideally, the cuff would be customized to fit the user and made of a softer material on the inner surface.
- The string used in the winch system on the motor shaft was a source of a few problems. After repeated use, the string became twisted and curled, which resulted in changes in tension. The loops came loose and sometimes wrapped itself up in the wrong section. String was selected as the material for its simplicity as a solution to turn the rotating unit relative to the stationary unit. It was convenient to attach to both the motor shaft and the mechanical structure. For future projects, a belt may be more suitable, although attachment may be more difficult.
- As discussed in the testing section, the cantilever created between Part A and Part B was probably a main source of torque transmission problems. This was removed from the quantitative testing, but when testing with the exoskeleton worn on the user, this was quite significant. Instead of generating a rotation, additional friction was being created.

CHAPTER 6:

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

At the start of the project, the objective was to design and implement a working product that was intuitively and reliably controlled, did not hinder the performance of other movements in daily activities, was compact in size, operated in a safe manner and was cost-effective. The exoskeleton was easy to control and did not have unaddressed safety hazards.

From the results of the testing, the exoskeleton was not able to produce a lot of additional power assistance throughout the movement. By decreasing the motor speed, the running torque improved. For a practical implementation, a stronger motor could be used to help increase the running torque. For the holding torque, although the amount of load it withstood was higher than what was possibly tested given the setup, only part of that resistance to the load can be attributed to the motor actuator. This was because of the results from the detent torque test, where a system with an unpowered motor still produced substantial holding torques.

While some of the choices in the project were made such that the theoretical design could be realized, they were not necessarily the most optimal solutions. With that in mind, based on the limited resources and materials, a workable solution was found such that the supination, pronation and holding requirements were successfully demonstrated, which was the primary objective of the project.

6.2 Recommendations and Further Development

As was the process of designing and implementing the solution throughout this project, there are many revisions that could be made to improve the current system. These points have been described in detail in Section 5.6. One major area of improvement would be the modelling of the pronation and supination biomechanics. In this solution, the motion was assumed to be axial. This simplification resulted in the system having some difficulties turning at certain angles since the user's forearm was resisting the axial rotation of the exoskeleton. The second major area of development would be to minimize torque transmission losses. Wherever there is contact between a rotating and stationary surface, the amount of friction must be minimized. As well, the string in the bidirectional winch system should be removed. Although it was a simple way to realize the idea, there were a number of problems with it. A belt is suggested for the next revision. As user safety and comfort is extremely important, one major improvement should also be to upgrade to customized forearm and wrist cuffs.

REFERENCES

[1] Kazerooni H, Steger R, Huang L. Hybrid control of the Berkeley lower extremity exoskeleton (BLEEX). Int.J.Robotics Res. 2006 05;25(5-6):561-73.

[2] Wege A, Hommel G. Development and control of a hand exoskeleton for rehabilitation of hand injuries. Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on 2005:3046-3051.

[3] Development of a hand motion assist robot for rehabilitation therapy by patient self-motion control. 2007 IEEE 10th International Conference on Rehabilitation Robotics, ICORR'07, June 12, 2007 - June 15; 2007; Noordwijk, Netherlands: Inst. of Elec. and Elec. Eng. Computer Society; 2007.

[4] Gupta A, O'Malley MK, Patoglu V, Burgar C. Design, control and performance of rice wrist: a force feedback wrist exoskeleton for rehabilitation and training. Int.J.Robotics Res. 2008 02;27(2):233-51.

[5] Dellon B, Matsuoka Y. Prosthetics, exoskeletons, and rehabilitation [Grand Challenges of Robotics]. Robotics & Automation Magazine, IEEE 2007;14; 14(1):30-34.

[6] O’Sullivan LW, Gallwey TJ. Upper-limb surface electro-myography at maximum supination and pronation torques: the effect of elbow and forearm angle. Journal of Electromyography and Kinesiology ;12(4):275-285.

[7] Gupta A, O'Malley MK, Patoglu V, Burgar C. Design, control and performance of rice wrist: a force feedback wrist exoskeleton for rehabilitation and training. Int.J.Robotics Res. 2008 02;27(2):233-51.

[8] Gopura RAR, Kiguchi K. Development of a 6DOF Exoskeleton Robot for Human Upper-Limb Motion Assist. Information and Automation for Sustainability, 2008. ICIAFS 2008. 4th International Conference on 2008:13-18.

[9] Development of an exoskeleton robot for human wrist and forearm motion assist. Second International Conference on Industrial and Information Systems - 2007; 9-11 Aug. 2007; Piscataway, NJ, USA: IEEE; 2007.

[10] Gopura RARC, Kiguchi K. Mechanical designs of active upper-limb exoskeleton robots: State-of-the-art and design difficulties. Rehabilitation Robotics, 2009. ICORR 2009. IEEE International Conference on 2009:178-187.