January 2014

Development Of A Prototype Movement Assistance System For Extravehicular Activity Gloves

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Recommended Citation

Hill, Tyler, "Development Of A Prototype Movement Assistance System For Extravehicular Activity Gloves" (2014). *Theses and Dissertations*. 1661.
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DEVELOPMENT OF A PROTOTYPE MOVEMENT ASSISTANCE SYSTEM FOR EXTRAVEHICULAR ACTIVITY GLOVES

by

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Bachelor of Science, California Polytechnic State University, 2012

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements

for the degree of
Master of Science

Grand Forks, North Dakota
December
2014

This thesis, submitted by Tyler Hill in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

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This thesis is being submitted by the appointed advisory committee as having met all the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

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Dean of the School of Graduate Studies

December 10, 2014
Date

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Tyler N. Hill
December 10, 2014

TABLE OF CONTENTS

CHAPTER

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to the members of my advisory committee for all of their guidance and support during this endeavor. Thank you Dr. Pablo de León, Dr. Vadim Rygalov, and Dr. Reza Fazel-Rezai. I would also like to extend my gratitude to the faculty of the Space Studies department for making my time in the master’s program at the University of North Dakota a fantastic experience.

For my mom Cheryl, my dad Reggie, and my
brothers Kyle and Jeff, thank you for always encouraging
me to shoot for the Moon.

ABSTRACT

Spacesuits utilized a rubberized layer of material to contain a pressurized atmosphere to facilitate respiration and maintain the physiologic functions of the astronaut residing within. However, the elasticity of the material makes it resistant to deformation increasing the amount of work required during movement. This becomes particularly fatiguing for the muscle groups controlling the motion of the hands and fingers. To mitigate this a robotic system was proposed and developed. The system built upon previous concepts and prototypes discovered through research efforts. It utilized electric motors to pull the index, ring, and middle fingers of the right hand closed, ideally overcoming the resistive force posed by the pressurized elastic material. The effect of the system was determined by comparing qualitative and quantitative data obtained during activities conducted with and without it within a glove box. It was found that the system was able to offload some of this elastic force though several characteristics of the design limited the full potential this device offered. None the less, the project was met with success and provides a solid platform for continued research and development.

CHAPTER I

INTRODUCTION

This document details the efforts made to design and develop a prototype movement assistance system for extravehicular spacesuit gloves. The primary reason for this undertaking stems from the continued impedance to movement of current spacesuit concepts. As will be detailed in the following text, this impedance stems from the core concept of maintaining a pressurized atmosphere around a human being to enable respiration and keep bodily fluids in a liquid state.

The original concept was developed at the start of the jet age in response to the pilot's need for a method of coping with the reduced pressures at high altitudes. The suits were only intended to pressurize during a loss of cabin pressure rather than facilitate movement in a pressurized state, a design principle which the Mercury spacesuits followed. However, with the challenge of landing on the Moon issued to the nation by President Kennedy NASA began experimenting with suit mobility. The Gemini program served as a testing ground for many of the technologies necessary for the subsequent Apollo program including the capability to work in the vacuum of space. Since the days of the first space race the pursuit of new techniques and materials has continued to produce spacesuits that allow astronauts greater freedom when working outside of their spacecraft. Even though there have been several advances in other areas of suit technology, one component that continues to lag or suffer is the glove. Creating an ergonomic garment for the hand that is able to contain the pressurized environment of the suit and still offer minimal impedance to movement continues to be a fantastic challenge. On average a 50% reduction in grip strength is experienced when working in the pressurized garment[1]. This is because facilitating the dynamic nature of the hand in a garment that is design to hold a specified volume via a flexible membrane highlights a material property that presents a rather large obstacle. As the human in the spacesuit moves their fingers and hand around it deforms the garment's shape and shifts the allocation of the internal volume. This causes the internal rubberized skin of the bladder, the "balloon," to experience a non-uniform distribution of force. Due to the elasticity of the material this deformation stretches the polymer chains in the rubber creating a restoring force that wants to return the glove to its neutral, or fabricated, shape[2]. The restorative force creates resistance to movement that fatigues the muscle groups responsible for manipulating the hand/wrist complex. The gloves used with the Extravehicular Mobility Units, EMU, on the International Space Station today employ techniques to reduce this resistance[3] though a nontrivial amount remains and can present issues during the six to eight hour timeline typical of present day extravehicular activities, or EVAs.

The reason this situation presents a particularly interesting conundrum is related to the fundamental concept behind the suit's development. As mentioned above NASA's spacesuits are able to trace their origins to pressure suits worn by early jet pilots which were intended for emergency use in the event of loss of cabin pressure. Maneuvering inside of what is essentially a human-shaped balloon is difficult, as noted by the Mercury

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[1] Melsoh, M., England, S., Benson, E., Thompson, S., Rajulu, S., “The Effects of Extravehicular Activity (EVA) Glove Pressure on Hand Strength”

[2] Ortiz, C., “Rubber Elasticity,” 3.11 Mechanics of Materials, Massachussettes Institute of Technology, 4 Nov. 2003.

[3] Graziosi, D., Stein, J., Ross, A., Kosmo, J., “Phase VI Advanced EVA Glove Development and Certification for the International Space Station”

astronauts, and not ideal for sustained operations in a reduced pressure environment. Yet it continues to be the core concept behind the garment's design because there has yet to be another reliable, cost effective method for creating this pressure that allows our predominantly liquid physiologies to survive in space. Mechanical counter pressure and hard-shell suits are two concepts that have been proposed in the past as substitutes however each have drawbacks that prevent their implementation. Mechanical counter pressure suits work on the principle of utilizing restricting fabrics to simulate the pressure of Earth's atmosphere on the surface of the skin. This keeps, along with thermal protection, keeps the various liquids in the body in their liquid state and helps to prevent dissolved gases from coming out of the blood stream and tissue. Should a portion of the body come into contact with the vacuum of space the epidermis and underlying tissue will balloon outward, a discomfort experienced by Joe Kittinger during his jump in August of 1960. Thus a restricting garment is required to retain functionality of the individual. However, manufacturing this garment has proved difficult with current materials. Advancements in material science are needed to create an "active" fabric that is able to adjust its material properties in response to the movement of the individual that wears it. Simultaneously facilitating movement in the joints and providing pressure on the surface of the skin all the while maximizing comfort[4]. Hard-shell suits, unlike mechanical counter pressure suits, are able to be manufactured using current materials and techniques[5]. Their utilization of hard components and air-tight joints, rather than an elastic membrane, throughout the suit allows

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[4] Chu, J., "Shrink-wrapping Spacesuits, Spacesuits of the future may resemble a streamlined second skin." MIT News Office, Massachusetts Institute of Technology, 18 Sept. 2014, http://newsoffice.mit.edu/2014/second-skin-spacesuits-0918.

[5] "Space Suit Evolution From Custom Tailored to Off-The-Rack," ILC Dover, NASA History, 1994, http://history.nasa.gov/spacesuits.pdf . pg 20.

movement to occur without changing the distribution of the internal volume. Thus the only force resistive to movement is the friction at the joint interfaces which only exists during motion and would place less strain on the muscles. However, hard-shell suits are much heavier than conventional suit concepts and the expense required to place them into orbit tends to outweigh the potential benefits. This is where movement assistance systems could offer a solution.

Movement assistance systems, commonly referred to as exoskeletons, that are able to detect and replicate the actions of a human being have the potential to reduce or mitigate the elastic force of the bladder during deformation. Such a system can completely remove the load of the elastic material felt by the individual within the suit creating the illusion that the glove has become completely pliant to deformation. The fatigue and reduction in dexterity experienced by astronauts conducting activities outside of the spacecraft can, theoretically, be eliminated and their utility enhanced. Thus the design and development of a system that is able to accomplish this while remaining unobtrusive and ergonomic was undertaken for this project. The research presented in the following section acts as a survey of the body of knowledge pertaining to exoskeleton devices intended for use in space. The relatively small number of documented prototypes unearthed indicated the infancy of this field thus the research was expanded to include related topics, such as anatomy and robotics, which aid in developing a foundation with which to build upon during the design process. Presented first is the associated research in anatomy, glove design, and robotics as it aids to build a conceptual understanding of the considerations that are carried into the design of this and other prototype exoskeleton systems.

CHAPTER II

LITERATURE REVIEW

Skeletal System

Seen in Fig. 1 the skeletal structure of the hand is the foundation for all other anatomical systems. It provides secure points for attaching other tissues and dictates the degrees of freedom and range of motion the appendage has. Prior to presenting the information acquired on the hand's anatomy, it is fundamental that the associated, unique terminology be understood. The terms that will be utilized include distal, proximal, palmar, dorsal, extrinsic, and intrinsic. Distal and proximal indicate whether the component being discussed is located toward the fingertips, distal, or the forearm, proximal. Palmar indicates that the component is located on the palm side of the hand while dorsal indicates it is located on the hand's backside. Extrinsic and intrinsic are primarily associated with the location of components of the muscular system, with extrinsic indicating a location external to the anatomical

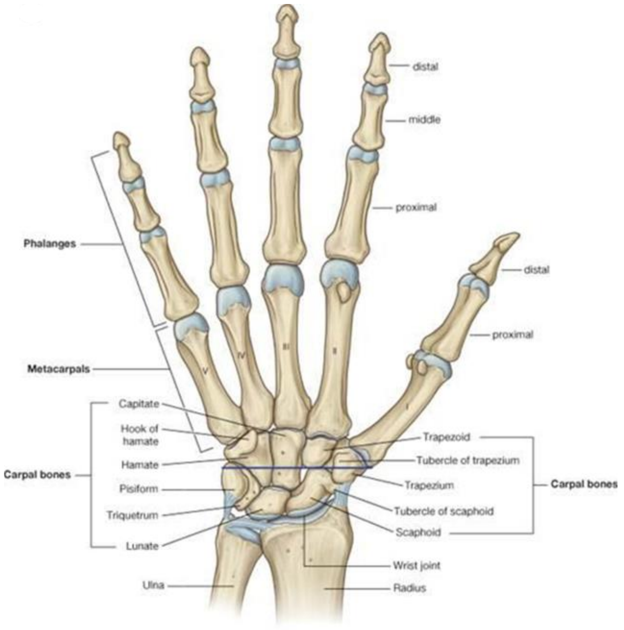

Figure 1. Diagram of the hand's skeleton with labels for each bone and group of bones shown[Calais-Germain].

region of the hand and intrinsic being within it. With this in mind the overview begins at the most proximal location of the appendage, the carpus region.

The carpus is the anatomical assembly that links the forearm to the rest of the hand and is commonly referred to as the wrist. The compound structure is convex on the palmar side forming the carpal arch. This is covered by the flexor retinaculum, a strong ligament band that forms the carpal tunnel through which a number of muscle tendons, blood vessels, and the median nerve pass under on their way to the fingers[6][7]. The carpus is comprised of eight small and uniquely shaped bones called the carpals. The designations of these bones are illustrated in Fig. 1. Each has a large articular surface for smooth, uniform movement with its neighbors. The carpal ligament structure acts as a net maintaining the bones' proximity and preventing them from slipping under one another during articulation. The carpal bones are grouped into two distinct rows based on location, proximal and distal. The proximal row, located closest to the forearm, consists of the scaphoid, lunate, triquetrum, and pisiform. It behaves as the interface between the forearm and hand because it allows the two to move independently of one another without injury by constantly adapting its shape. The distal row is comprised of the trapezium, trapezoid, capitate, and hamate. Unlike the proximal row, the movement of the distal row is more restricted, tied to that of the metacarpals[8]. The area where the two rows meet is known as the mid-carpal joint. Each section of this joint has an articular capsule that is, more or less, joined to the others via a complex ligament structure surrounded by a continuous synovial

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[6] Calais-Germain, B., "Chapter 5: Wrist & Hand," *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

[7] Tyldesley, B., Grieve, J. I., "Chapter 6: Manipulative Movements The Forearm, Wrist & Hand," *Muscle Nerves & Movement in Human Occupation*, Blackwell Science Ltd., 2002, pp. 98-120

[8] Calais-Germain, B.

membrane[9]. The range of motion of the wrist is measured at the joint between the proximal carpals and radial bone of the forearm and is typically 180 degrees in total, 90 degrees of flexion and extension respectively[10]. Moving toward the fingers the next group of bones encountered are the five metacarpals and the region that joins them to the carpal bones known as the carpametarpal, or CMC, joint.

The metacarpals provide the structural base for the palm as well as the attachment points for several intrinsic muscles. A complete diagram of the metacarpal bone is shown in Fig. 2. Each metacarpal bone, except the thumb, has a base that is relatively flat and roughly quadrangular with facets that allows for articulation with the respective carpal and adjacent metacarpal bones. The flat articular surfaces of the carpametacarpal joint allow slight sliding during flexion and extension movements of the hand. The range of this sliding motion increases from the index metacarpal to the pinky and is caused by the ring and pinky finger CMC joints lying slightly oblique to the others. This creates the depression, or cupping, of the palm that appears during several types of grasping motions[11]. The articular surface of the thumb's CMC joint is not flat like the other digits. Instead it forms a saddle joint with the trapezium carpal bone, allowing the thumb to move through three spatial planes[12]. This characteristic is the reason our thumbs are opposable,

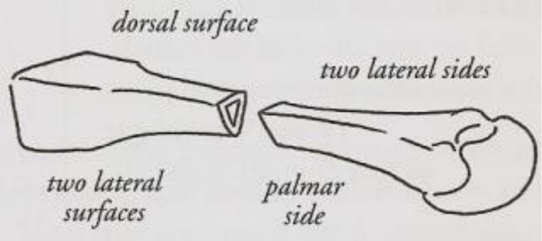

Figure 2. Cross-section of the metacarpal bone illustrating the triangular shape, flat base, and secular head[Calais-Germain]

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[9] Calais-Germain, B., "Chapter 5: Wrist & Hand," *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

[10] Clarkson, H. M., *Musculoskeletal Assessment Joint Range of Motion and Manual Muscle Strength*, Second Ed., Lippincott Williams & Wilkins, 2000, pp. 198-228, 257-62.

[11] Calais-Germain, B.

[12] Calais-Germain, B.

or able to move in opposition of the other digits making grasping and pinching actions possible. The metacarpal bone shaft is triangular which aids in accommodating the intrinsic muscles of the hand and increases structural integrity[13]. Distal to the shaft is the head which displays a convex articular surface covered in cartilage and two round nodules that serve as pathways for tendons. The metacarpal heads meet with the bases of the next group of bones, known as the phalanges, creating the metacarpaphalangeal, or MCP, joint.

As shown in Fig. 1 the phalanges are broken down into proximal, middle, and distal phalanxes, aside from the thumb which only has a proximal and distal phalanx. The bases of the proximal phalanxes are round and concave creating a hinge with the head of associated metacarpal that allows for flexion, extension, abduction, adduction, and slight rotation as illustrated in Fig. 3. The range of passive extension is greater than that of active extension because the MCP joint capsule is slightly slack in this plane of motion[14]. The MCP joint of the thumb varies slightly from the other digits in that it is larger and the ligament capsule is not as taught allowing for small amounts of rotation. Furthermore, there are two small bones embedded on the palmar side to serve as tendon attachment points for the muscular system[15]. The MCP joint capsules of all of the digits are reinforced by the palmar and collateral ligaments which reside on the

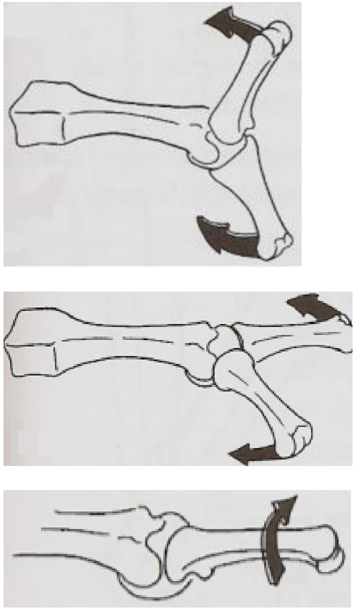

Figure 3. Movement characteristics of the joint between the proximal phalanx and the metacarpal bone[Calais-Germain].

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[13] Calais-Germain, B., "Chapter 5: Wrist & Hand," *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

[14] Calais-Germain, B.

[15] Calais-Germain, B.

palmar and lateral surfaces of the finger respectively[16]. The palmar ligament is composed of a dense band of tissue and helps prevent over-extension while protecting the joint during grasping actions. The collateral ligaments originate from nodules on the dorsal side of the proximal phalanx head so they tend to be slack in extension and taut during flexion[17]. This is the reason the MCP joints are able to passively abduct and adduct when the hand is in a neutral position allowing a grasping action to adapt to the shape of the object. Conversely when the joints are flexed, as mentioned previously, there is almost no passive movement creating a stable grip. The shaft of the proximal phalanx is cylindrical and its head is grooved like the wheel of a pulley. The base of the subsequent middle phalanx is concave with a crest down the middle to match the shape of the proximal phalanx head[18]. The joint between the proximal and middle phalanges is the proximal interphalangeal, or PIP, joint. It permits flexion and extension however, unlike the MCP joints, there is little dorsal articular surface so hyperextension is essentially nonexistent[19]. The shaft and head of the middle phalanx are the same as those of the proximal just reduced in size. The base of the distal phalanx is contoured to fit the head of the middle phalanx creating the distal interphalangeal, or DIP, joint which is near identical to the PIP aside from the noted occurrence that most individuals possess a degree of passive hyperextension[20]. The DIP joint of the thumb is similar to the other digits' with the exception of being more massive[2]. The head of the distal phalanx has a protrusion on the palmar side that forms the area of

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[16] Calais-Germain, B., "Chapter 5: Wrist & Hand," *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

[17] Levangie, P. K., Norkin, C. C., *Joint Structure and Function: A Comprehensive Analysis*, Fourth Ed., F. A. Davis Company, Philadelphia, PA. 2005, pp. 321-46

[18] Levangie, P. K., Norkin, C. C.

[19] Calais-Germain, B.

[20] Calais-Germain, B.

the finger tip. Each of the interphalangeal joints has palmar and collateral ligaments structurally and functionally identical to those of the MCP joints.

Muscular System

The muscular system is the “other half” to the kinematics of the hand. Force transmission from a muscle is either classified as local or remote. Local transmission is when the muscle fibers are attached directly to the bone they are actuating and is a characteristic of the intrinsic muscles of the hand. Remote transmission is when the muscles use tendons to deliver force to the appropriate area usually because they are located externally of the corresponding anatomical region. As stated previously this is a characteristic of the extrinsic muscle group. The muscles which actuate the wrist are not covered because the scope of the paper focuses on enhancing the utilization of the astronaut’s hands which primarily pertains to actuation of the phalanges.

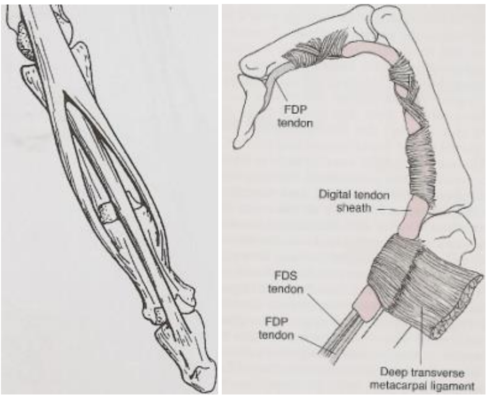

Figure 4. Layering of the flexor digitorumprofundus, FDP, and flexor digitorumsuperficials, FDS, tendons (left) and the ligament sheaths (right) that secure them to the bone to prevent bowstringing during flexion[Calais-Germain, Levangie].

Starting with the extrinsic muscles we find nine individuals that can be further divided into three groups based on their function; flexors, extensors, and extrinsic thenar muscles. The flexors and extensors, intuitively, are responsible for flexion and extension of the fingers. The extrinsic thenar muscles work with the intrinsic thenar muscles to actuate the thumb through its complex range of motions. Within the flexor subcategory are the flexor digitorumprofundus and flexor digitorumsuperficialis. The digitorumprofundus muscle is responsible for flexing the distal phalanxes of each finger and assisting in flexion of the middle and proximal phalanxes. The muscle originates near the elbow and passes along the medial and anterior surfaces of the ulna[21]. The muscle splits into four tendons which pass through the carpal tunnel and insert into the distal phalanxes of the fingers. The flexor digitorumsuperficialis lies on top of the profundus and passes through the carpal tunnel splitting into four tendons which in turn split into "Y" heads and insert on the sides of the middle phalanges[22]. The "Y" shape allows the profundus tendon to pass from below to insert on the distal phalanx. The layering of the supericialis and profundus tendons is shown in Fig. 4 as well as the protective tendon sheaths and fibrous tunnels which hold them close to the skeleton to prevent bowstringing during flexion. The flexor digitorumsuperficialis is responsible for flexing the middle phalanx and assists in flexion of the proximal phalanx.

The extrinsic extensor group is comprised of the extensor digitorum, extensor indicis, and extensor digitiminimi[23]. The extensor digitorum passes down the back of the forearm and splits into four tendons, each of which split into three bands as shown in Fig 5. The central band inserts on the posterior base of the proximal and middle phalanges while the two lateral bands unite at

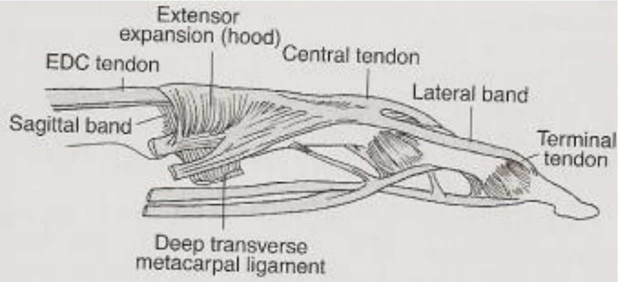

Figure 5. The extensor digitorum, EDC, tendon is shown splitting into the central, lateral, and terminal bands as well as the extensor hood[Calais-Germain].

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[21] Calais-Germain, B., "Chapter 5: Wrist & Hand," *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

[22] Calais-Germain, B.

[23] Calais-Germain, B.

the base of the distal phalanx. This muscle assists in extension of the interphalageal joints along with the lumbricals and interossei intrinsic muscles. The extensor indicis is a smaller muscle originating from the ulna near the wrist and its tendon joins that of the extensor digitorum leading to the index finger reinforcing the action of the tendon to this particular finger. The last of the group is the extensor digitiminimi which is located next to the extensor digitorum and its tendon joins that of the digitorum leading to the little finger reinforcing its action in a manner similar to that of the extensor indicis[24][25]. The last group of extrinsic muscles is the extrinsic thenar group. Shown in Fig.6 it is comprised of the flexor pollicislongus, abductor pollicislongus, extensor pollicis brevis, and extensor pollicislongus. The flexor pollicislongus flexes the interphalangeal, MCP, and CM joints of thumb and assists in wrist flexion and abduction. The muscle originates from the anterior of the ulna and its tendon passes through the carpal tunnel and inserts on the base of the distal phalanx of the thumb. The abductor pollicislongus is responsible for anteromedial movement of the thumb and assists in flexion of the wrist and abduction of the thumb. The head of the muscle arises

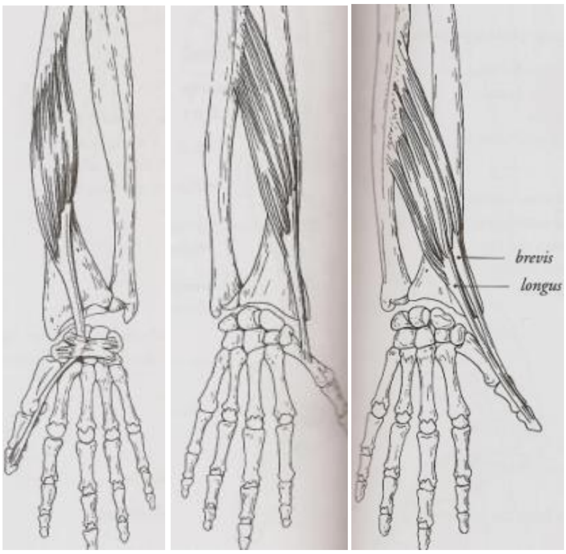

Figure 6. Illustrations of the extrinsic thenar, thumb, muscles which include the flexor pollicis longus (left), abductor pollicis longus(middle), and extensor pollicis with the long and short tendons labeled (right)[Calais-Germain].

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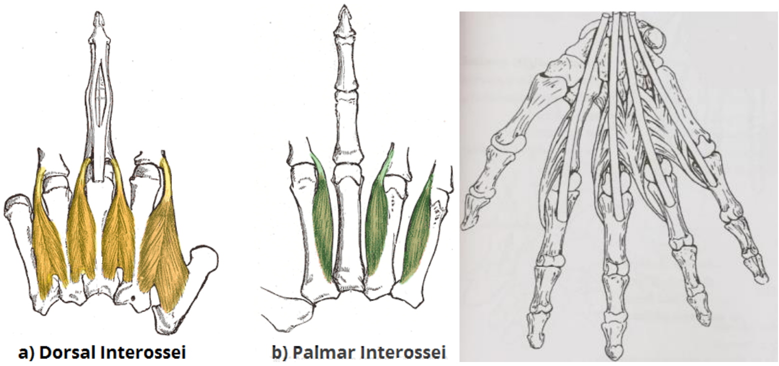
[24] Seller III, J., "Chapter 2: Anatomy," *Essentials of Hand Sugery, American Society for Surgery of the Hand*, Lippincott Williams & Wilkins, 2002, pp. 5-20.

[25] Calais-Germain, B., "Chapter 5: Wrist & Hand," *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

from the posterior surfaces of the ulna and radius and its tendon passes under the extensor retinaculum and inserts of the lateral base of the thumb's metacarpal. The extensor pollicis brevis and longus muscles originate along the ulna and insert on the base of the proximal and distal phalanges of the thumb respectively. The pollicislongus extends the carpometacarpal, metacarpaphalangeal, and interphalangeal joints of the thumb. The pollicis brevis assists with the extension of the carpometacarpal and metacarpaphalangeal joints.


a) Dorsal Interossei

b) Palmar Interossei

Figure 7. Palmar and dorsal interossei (left) and lumbrical (right) intrinsic muscles[Calais-Germain].

The intrinsic muscles, as stated previously, exist within the anatomical region of the hand and may be grouped by function just like the extrinsic muscles. These groups are the interossei, lumbrical, hypothenar, and intrinsic thenar muscles. The interossei, shown in Fig. 7 with the lumbricals, consist of seven muscles located between the metacarpal bones, four dorsal and three palmar. They are responsible for abducting or spreading the index, middle, and ring fingers away from the hand's midline. They also assist in flexion at the metacarpophalangeal joints and in extension of the interphalangeal joints[26][27]. Each has four contact points located at the base of the proximal phalanx, the identical fibers on the adjacent interosseous, and two on the edges of the extensor digitorum tendon at the

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[26] Calais-Germain, B., "Chapter 5: Wrist & Hand," *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

[27] Seller III, J., "Chapter 2: Anatomy," *Essentials of Hand Sugery, American Society for Surgery of the Hand*, Lippincott Williams & Wilkins, 2002, pp. 5-20.

proximal and middle phalanges[28]. On top of the palmar interossei are the four lumbrical muscles. This group originates from the tendons of the flexor digitorumprofundus just distal of the carpal tunnel and insert on the tendons of the extensor hood. The extensor hood, or extensor expansion, is part of the tendons structure of the extensor digitorum distal to the metacarpals[29][30]. The lumbricals collectively flex the metacarpophalangeal joints and extend the interphalangeal joints.

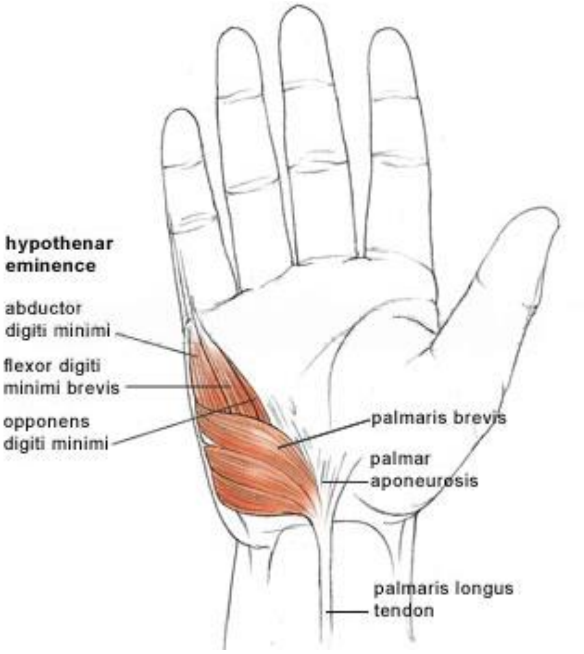

Figure 8. The intrinsic muscles of the 5th finger which reside in the hypothenar eminence and aid in flexion, abduction, and opposition with the thumb.

Next are the hypothenar muscles which are responsible for assisting the extrinsic flexor and extensor tendons attached to the pinky as well as move the finger in opposition with the thumb for grasping actions. Each of the muscles is illustrated in Fig. 8. The first muscle within this subgroup is the oppenensdigitiminimi which aids in moving the pinky toward the thumb to create a curved palm for grasping actions. The oppenensdigitiminimi originates from the flexor retinaculum and inserts on the medial surface of the pinky[31]. The next muscle is the flexor digitiminimi which is responsible for the flexion of the pinky at the MCP joint toward the palm. It shares the

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[28] Calais-Germain, B., “Chapter 5: Wrist & Hand,” *Anatomy of Movement*, Estland Press Inc. 2007, pp. 159-89.

[29] Calais-Germain, B.

[30] Levangie, P. K., Norkin, C. C., *Joint Structure and Function: A Comprehensive Analysis*, Fourth Ed., F. A. Davis Company, Philadelphia, PA. 2005, pp. 321-46.

[31] Levangie, P. K., Norkin, C. C.

same origin as the oppenensdigitiminimi and inserts at the base of the proximal phalanx. The final muscle in this subgroup is the abductor digit minimi which abducts the pinky away from the centerline of the hind and aids in flexion of the proximal phalanx. The muscle head is attached to the flexor retinaculum and the pisiform carpal bone and inserts at the same location as the oppenensdigitiminimi.

The final group of intrinsic muscles, shown in Fig. 9, is that which lie within the thenar prominence, also known as the intrinsic muscles of the thumb. The first of which is the adductor pollicis which has two sets of muscle fibers, the oblique and transversus which form a web running from the trapezoid and capitate carpals and the second and third metacarpals to the medial base of the proximal phalanx of the thumb. These sets of fibers move the metacarpal of the thumb toward that of the index finger and flex the thumb's MCP joint. The next muscle also has two sets of fibers however these are layered on top of one another. The deep and superficial flexor pollicis brevis tendons originated from the carpal area and flexor retinaculum and insert on the base of the proximal phalanx and the metacarpal of the thumb near the MCP joint. The flexor pollicis brevis brings the thumb's metacarpal bone toward the hand's midline as well as rotates it to face the other fingers in preparation for opposition. During the

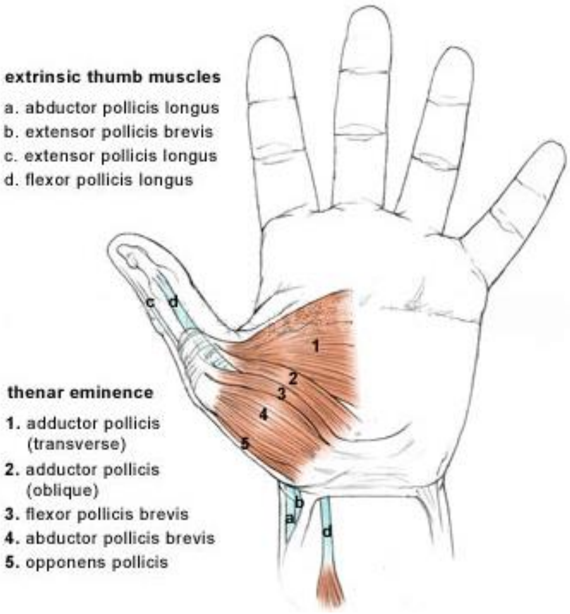

Figure 9. The intrinsic muscles of the thumb, thenar eminence, are shown along with their layering with the extrinsic muscles of the thumb.

rotation the muscle also flexes the proximal phalanx of the thumb. Third in the group is the oppenespollicis which brings the metacarpal toward the surface of the palm and aids in its rotation to create the required movements for grasping actions. The muscle rises from the trapezoid carpal bone and flexor retinaculum and inserts along the anterior middle surface of the metacarpal. The final muscle in the thenar group is the abductor pollicis brevis which originates from the flexor retinaculum, trapezoid and scaphoid bones and inserts on the base of the proximal phalanx next to the flexor pollicis brevis. It is responsible for pulling the metacarpal toward the midline of the hand and flexes the MCP joint.

Phase VI Glove Program Development

Since the early 1980's the glove design adopted for the Shuttle program had undergone several evolutions to adapt to changing space based tasks. It started with the 1000 series glove and continued to the 4000 series which directly preceded the Phase VI glove. Throughout these iterations the design of the glove itself had essentially remained unchanged and each generation focused on integrating new materials to find a balance between durability and tactility[32][33]. The material changes did aid in creating a better glove but in the early 1990's it was realized that the current design and its performance capabilities had been pushed as far as it could. A new design and textile patterning philosophy was needed to meet the challenge of the ISS assembly and thus began the road to the creation of the Phase VI glove program.

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[32] Jordan, N. C., Saleh, J. H., Newman, D. J., "The extravehicular mobility unit: A review of environment, requirements, and design changes in the US spacesuit," Acta Astronautica 59, 2006, pp. 1135-1145.

[33] Graziosi, D., Stein, J., Ross, A., Kosmo, J., "Phase VI Advanced EVA Glove Development and Certification for the International Space Station," Society of Automotive Engineers, 2001-01-2163

Design points from the latter production models of the 4000 series were taken and implemented in the subsequent Phase IV glove. It was designed to operate at 8.3 psig making compatible with a "zero-prebreath" system in an effort to eliminate lengthy pre-breaths to maximize EVA time for ISS assembly. Fit improvements were also developed by creating the bladder and restraint layer tooling directly from casts of the astronaut's hands, a strategy that also increased finger tactility. The restraint layer saw design improvements in the form of full fabric fingers, new seam configuration, palm bar, and segmented palm plates to create the desired shape while pressurized[34]. The wrist of the glove was created as a four ring rolling convolute joint providing constant volume during movement and promoting stable low torque motion[35][36]. The first flight ready prototype of the Phase IV program, dubbed the 5000 series glove, was worn by Jerry Ross on STS-37 where some complexities were noticed with the new wrist design and weight distribution[37]. Development and experimentation continued under the 5000 series glove project including testing the viability for advanced manufacturing methods such as the Laserscan Process Development that is the core of the Phase VI program. This process uses laser scanning to create a computerized rendering of a subject's hand cast which is then manufactured using a stereolitography apparatus, or SLA. The SLA 3-dimensionally prints the tooling derived from the laser scan by bouncing a UV laser off of photo-reactive resin. An example of this

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[34] Graziosi, D., Stein, J., Ross, A., Kosmo, J., "Phase VI Advanced EVA Glove Development and Certification for the International Space Station," Society of Automotive Engineers, 2001-01-2163

[35] Jordan, N. C., Saleh, J. H., Newman, D. J., "The extravehicular mobility unit: A review of environment, requirements, and design changes in the US spacesuit," Acta Astronautica 59, 2006, pp. 1135-1145.

[36] Graziosi, D., Stein, J., Ross, A., Kosmo, J.

[37] Graziosi, D., Stein, J., Ross, A., Kosmo, J.

is shown in Fig. 10. In addition, the 3-dimensional computer model was used to derive patterning methods to create a restraint layer that more accurately represented the shape of the hand.

These technologies and techniques were further refined under the direction of the Phase V program, for which Story Musgrave was chosen as the experimentation subject. Improvements to the laser scan technology lead to more accurate renderings of the hand and improvements to computer aided design, CAD, software meant higher resolution models could be produced. These advancements lead to the development of a minimum easement bladder/restrain system to lower the internal volume and force required for operation. The palm bar and plate design were carried over from the 5000 series glove however the segmented palm was exchanged in favor of a one-piece composite plate reducing the glove's bulk. The wrist joint was lightened by substituting titanium and graphite/epoxy composite materials for the rolling convolute design. The last feature was the development of an on-orbit replaceable unit, or ORU, thermal and micrometeorite garment manufactured from a knit fabric palm molded to the shape of the bladder reducing the number of seams in and bulk of the garment.

Figure 10. Images of the hand cast (left) and 3D printed tooling (right) derived from it during the manufacturing process of the Phase VI glove[Graziosi].

After the Phase V came the Phase VI program which placed a new focus on improving the cost to performance ratio of the advanced glove development efforts. NASA decided that the extravehicular mobility unit, or EMU, used on EVA tasks would operate at a reduced pressure of 4.3 psig for the foreseeable future. This allowed the softgoods, textile approach to meet the high performance requirements of the advanced glove programs negating the need for a wrist joint constructed of hard components. The Phase VI program would consolidate all of the advanced knowledge gained through the previous programs and pursue the development of an advanced softgoods wrist to create customized gloves that offer improved dexterity and reduced fatigue compared to the previous generations[38].

In December of 1998 the newly developed Phase VI gloves were flown on their first mission with astronaut Jerry Ross who reported that their performance was superior to the previous 4000 series that had long been the standard[39]. The glove underwent two flights, STS-82 and STS-88, after each it was inspected and found to be in excellent condition certifying it to serve on a single Shuttle mission for all EVA's including contingencies. Certification efforts continued as the glove underwent a battery of tests to make sure it measured up to the standards put in place with the ISS program including operating tools, connecting electrical and hydraulic lines and movement along hand rails. Today the Phase VI glove serves as the standard onboard the ISS.

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[38] Graziosi, D., Stein, J., Ross, A., Kosmo, J., "Phase VI Advanced EVA Glove Development and Certification for the International Space Station," Society of Automotive Engineers, 2001-01-2163

[39] Graziosi, D., Stein, J., Ross, A., Kosmo, J.

Phase VI Glove

The design features of the Phase VI glove include the aforementioned softgood wrist and improved bladder, restraint and TMG layers. Shown in Fig. 11 the wrist design uses a two gimbal-ring system closely integrated with the garment’s fabric that isolates flexion/extension from abduction/adduction promoting smoother movement and control of the joint. The upper ring of the assembly is oval shaped mimicking the cross-section of the wrist to increase tracking of the glove to the hand while the lower wring is circular with adjustable pivot heights for efficient load transfer. The softgoods of the wrist include webbing between the rings to prevent side impact failures and convolute patterning optimized in size and shape to maximize range of motion and stabilize low torque movements. Lacing is used to tightly integrate the gimbal rings and softgoods creating a joint shape that can be tightly controlled and the volume remains nearly constant. The bladder of the Phase VI glove is composed of urethane and exhibits little to no wrinkling when integrated into the glove system. This significantly improves the glove’s fit and performance of the end user. As seen in Fig. 10, convolute ridges were added to the dorsal side of each digit providing extra material run length during flexion to reduce the force required by each finger. A fabric liner

Figure 11. Restraint and TMG layers of the Phase VI glove with labels detailing the various components[Graziosi].

is included in the wrist to prevent abrasion of the crew member's arm and increase the lifetime of the bladder. A one-piece fabric reinforced flange is also incorporated to prevent bolt hole tear-outs during installation and removal of the glove at the disconnect.

The restraint layer of the glove is designed to capture, as much as possible, the anthropomorphic features of the hand. The Laserscan capabilities of the Phase V program were refined along with the tooling and textile patterning philosophy to promote a better fit. This involved the development of new anthropometrically based algorithms to reposition the thumb promoting a better handgrip. The construction of the garment involves pleated, lightweight polyester fabric creating finger and thumb joints which decrease torque and increase tactility. The stainless steel palmbar is placed in the crease of the hand and provides palm control when the MCP joints of the hand are flexed. The positioning of the palm plate has also been improved to prevent ballooning and its curvature optimizes the perimeter shape of the hand improving grip while minimizing bulk.

Lastly the TMG of the Phase VI glove incorporates several improvements including increased size, new materials and pattern philosophy, improved insulation, and an active heating system. The garment also carries over the ORU capability from the previous generation, a function that is a requirement for the EMUs onboard the ISS. The increase in garment size prevents pressure loads from transferring from the restrain layer to the TMG yet does not encumber the user because its shape is defined directly by the restraint layer of the glove. The fabric used in the palm area of the TMG is a specially woven knit material which stretches allowing the fabrication of a one-piece palm. This means no seams exist in the working area of the glove further reducing bulk. The improved thermal system includes felt insulation in areas of prime surface contact and resistive heating elements in the fingertips that are able to be toggled on/off by the astronaut to optimize thermal comfort.

Glove Effects on Dexterity

As briefly stated in the Introduction, in spite of the marked improvements in glove design and technology the astronaut is still required to exert greater than normal levels of force when moving. This causes fatigue and can limit the astronaut's ability and overall length of an EVA. A study was performed at the Lyndon B. Johnson Space Center in Houston, TX to quantify the effects the glove has on daily operation[40]. Tests were carried out to determine the maximum force delivered during a grip, lateral pinch and pulp-2 pinch under three different conditions: bare-handed, gloved without the TMG, and gloved with the TMG. The lateral pinch is performed by squeezing the thumb against the middle of the index finger while the pulp-2 involves pressing the thumb against the tip of the index finger. During the gloved portion of the tests the participants performed the tasks under pressurized and unpressurized conditions to isolate the effect of the pressure differential. As a percentage of bare-handed strength the results showed that the TMG reduced grip strength to 55% unpressurized and 46% when pressurized. When the TMG was removed unpressurized grip strength increased to 66% and pressurized increased to 58%. Lateral pinch seemed to be unaffected by the increased pressure or the TMG registering about 85% of bare-hand strength for all scenarios. The pulp-2 pinch increased beyond the control scoring 122% for unpressurized and 115% pressurized without the TMG. With the TMG

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[40] Melsoh, M., England, S., Benson, E., Thompson, S., Rajulu, S., "The Effects of Extravehicular Activity (EVA) Glove Pressure on Hand Strength," NASA.

the pulp-2 pinch was 115% of bare-handed strength for both pressure conditions. A hypothesis for this occurrence is that the pulp pinch uses the neutral position of the glove to the user's advantage. As seen in Fig. 12 the subject has to increase the spacing between the index finger and the thumb thus the force exerted on the sensor is a combination of the restorative force of the glove and the person. For the unpressurized test this may not initially make sense however the restorative force in the glove is also derived from the properties of the materials because they are manufactured in a certain position and deviations create stress within them creating an elastic restorative force.

A similar study was performed by the Johnson Space Center in conjunction with the University of Nebraska in 1993 which focused on developing pressure performance curves for three different types of glove[41]. During the study several participants were asked to complete several different variations of grip and pinch strength tests as well as timed tasks involving the manipulation of several small objects. The objective of the study was to determine at what pressure differential task performance becomes significantly hindered. This would in turn indicate whether or not an operating pressure above the current 4.3 psi could be used on-orbit to reduce prebreath times. The results showed a 50% reduction in grip strength and approximately a 10%

Figure 12. Pulp-2 pinch test performed to determine the effects of the EVA on force output[Melsoh].

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[41] Bishu, R. R., Klute, G., *The Effects of Extravehicular Activity (EVA) Gloves on Human Performance*, International Journal of Industrial Economics, ELSEVIER, 5 August 1994.

reduction in pinch strength when each of the gloves was donned. When the gloves were brought to the standard operating pressure of 4.3 psig in the glove box a deduction on the order of 10-12% was noted in the strength measurements and pinch strength seemed relatively unaffected. As the pressure increased to 6.3 and 8.3 psig a further reduction of 3-4% was seen. The timed dexterity tests saw an average increase of 50% at 3.2 and 4.3 psi from the barehanded results, though each glove type offered a different level of performance. At the higher operating pressures of 6.3 and 8.3 psig the time to complete the tasks involving small object manipulation nearly tripled while the tasks involving larger objects increased approximately 15% in time.

These studies show strong relations in their results. Both saw a reduction in grip strength of approximately 50%, the Johnson Space Center study was about 5% higher, and relatively no change in pinch performance. The latter study stipulated that the pinch test anomaly could be the result of the extra cushion at the point of contact. The timed dexterity tests were solely carried out in the University of Nebraska study, so a comparison can’t be made at this time, however it does provide an additional metric with which to judge how human performance is affected by the pressure differential and the glove itself. These quantified effects of the pressure differential and glove bulk on participant performance provide a useful metric by which the effectiveness of an assistive robotic system may be judged. Furthermore, they provide cues for the design itself. The grip strength tests showed the greatest drop in performance when the pressure differential increased indicating actions involving bulk motion of the glove may benefit the most from an assistive system. This gives priority to certain joints and degrees of freedom which in turn help develop the list of requirements for the system. The lateral pinch was only affected by the addition of the glove, and the pulp pinch increased in strength. While the effects due to the bulk of the glove may not be solvable through the addition of a mechanical system they are still noteworthy and need to be accounted for as glove design continues to evolve.

Feasibility of Integrating Robotics Into an EVA Glove

The concept of integrating robotics into spacesuit gloves may be viewed as obscure and unnecessary because it adds complexity to a simple and proven garment. However, the idea has continued to receive attention as actuators and electronic components shrink in size. A pair of feasibility studies were published in 2010 and 2012 discussing this concept paying close attention to the restraints and requirements a system of this category would have to meet. The studies were conducted at the Italian Institute of Technology, the Department of Control and Computer Engineering, and the Department of Mechanical and Aerospace Engineering in Torino, Italy[42][43]. Among the topics discussed in the papers are concerns of the space environment, limitations imposed by the glove, methods to ensure the system does not impinge on the working surface of the glove, ergonomics, joint characteristics, control concepts, and options for the structure, actuators and sensors. The thermal and radiation environments in open space pose hardships on electrical and mechanical components, such as electro static discharge and cold welding, which can lead to their failure. However the methods of hardening components against radiation, spacing out conductive surfaces to prevent arcing and operating in extreme temperatures are well

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[42] Favetto, A., Chen, F. C., Ambrosio, E. P., Manfredi, D., Calafiore, G. C., “Toward a Hand Exoskeleton for a Smart EVA Glove,” International Conference on Robotics and Biomimetics, IEEE, 2010.

[43] Favetto, A., Ambrosio, E. P., Appendino, S., Battezzato, A., Chen, F. C., Manfredi, D., Mousavi, M., Pescarmona, F., “Embedding an Exoskeleton Hand in the Astronaut’s EVA Glove: Feasibility and Ideas,” International Journal of Aerospace Sciences 2012, I(4): 68-76.

understood by engineers working in the space industry. Developing a system with moving components to meet the requirements imposed by the glove, on the other hand, is not as well understood and attention is paid to the ideas proposed in this area. Favetto[44][45] states that the small envelope and continuous movement seen by the garment indicates that reducing the size and mass of the components will create a better user experience. This does not preclude the use of larger, more powerful actuators as they can be remotely located along the arm and deliver force to the desired location via a cable system. For the force to be delivered effectively tension has to be sustained in the cable even across joint boundaries such as the wrist. Applying the force of the actuator in the proper direction is a nontrivial task as well because the working area, palm, of the glove should be kept as free as possible to not hinder the ability of the astronaut to complete their task. This means that the assisting force for flexing the fingers of the glove should come from a pushing force on the back of the digits rather than palmar cables pulling them closed. The former requires a system of pushrods that allow the fingers to flex yet are able to deliver the desired force to the proper phalanx creating a higher mechanical profile above the finger and making the system bulky. The latter would make for a much simpler system because as long as the cable is secured to the glove at each phalanx the structure of the robot is that of the human hand eliminating the need for additional hinge mechanisms. The actuators suggested by the studies were traditional electric motors due to their proven reliability with piezoelectric motors as a more exotic choice because they offer consistent, high torque performance in

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[44] Favetto, A., Chen, F. C., Ambrosio, E. P., Manfredi, D., Calafiore, G. C., "Toward a Hand Exoskeleton for a Smart EVA Glove," International Conference on Robotics and Biomimetics, IEEE, 2010.

[45] Favetto, A., Ambrosio, E. P., Appendino, S., Battezzato, A., Chen, F. C., Manfredi, D., Mousavi, M., Pescarmona, F., "Embedding an Exoskeleton Hand in the Astronaut's EVA Glove: Feasibility and Ideas," International Journal of Aerospace Sciences 2012, I(4): 68-76.

small packages and are able to move freely should power be lost. Sensor packages recommended are flex or bend sensors which offer a simple and reliable way to accurately gather data. Care needs to be taken when interpreting the observed analogue signal as radiation and nearby components can put noise into the system if the wires are not properly shielded and an algorithm is not used to smooth it out.

Another key design point is the degrees of freedom replicated by the system. Unless the apparatus is utilizing the skeleton of the hand for its structure as described previously, the more degrees of freedom emulated by the machine the more obtrusive it becomes. Furthermore, the hand has 23 degrees of freedom and attempting to replicate all of them is extremely difficult. Thus it is logical to determine which ones are necessary for the desired application based on the most common movements performed during it. While Favetto does not suggest which ones are pertinent for tasks completed during EVA’s this was determined by watching video recordings from the astronaut’s helmet mounted cameras and will be elaborated on in the Conclusions. The final significant point discussed in the studies is the unique requirement imposed by the hand on any structural element used around the joints of the phalanges. Though it has been stated that creating a system that uses the skeleton as the structural foundation is simpler, if an exoskeleton style apparatus is desired then the joint characteristics of the fingers have to be considered. As stated in the Anatomy section, the joints of the fingers are not classic hinges because the loose joint capsule and characteristics of the articular surfaces allows for a certain degree of slippage and passive rotation. This means that the center of rotation is constantly moving through the whole range of motion and unless the structure can accommodate this it will interfere with the movements of the user. The solution proposed by Favetto, shown in Fig. 13, is the implementation of a scissor-style “four bar mechanism” that is able to rotate around the instantaneous center of rotation and accommodate this movement.

Overall, there are several similarities between the system concept in these two studies and those mentioned in this section and related technologies. This is due to the role in which the assistive system is attempting to fulfill and the technology available to researchers at this point in time. The advantage to this is it provides a narrower scope and an informational platform with which to build off of to create a system that can address shortcomings of the previous technology such as size or capability.

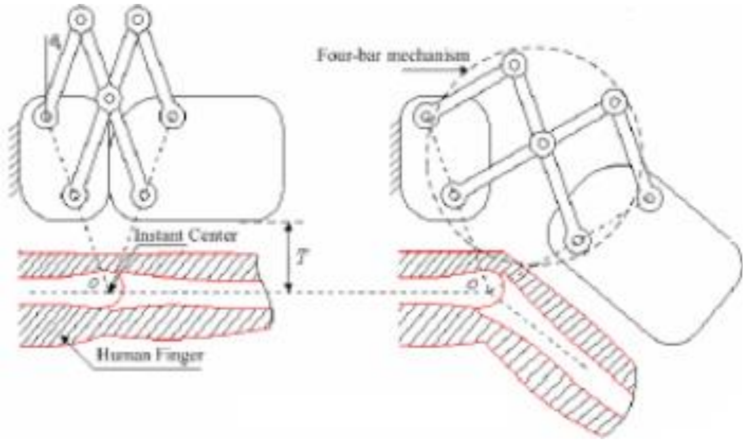

Figure 13. Scissor-style “four bar mechanism” proposed to overcome the abnormal hinge movement of the interphalangeal joints[Favetto, Chen].

Previously Developed Prototypes

In addition to the studies conducted on EVA glove robotics, prototypes have been developed that experiment with a different actuation techniques and features that increase tactility as well as dexterity. The examples selected for further study include a pneumatic SkilMate finger system, an electric SkilMate finger with tactile feedback, and a glove with a powered metacarpal joint. SkilMate is a brand of wearable intelligent machines developed through collarborative efforts by the Toyota Technological Institute, the

Shimizu Corporation, the Denso Corporation, and the Intelligent Robotics Laboratory in Japan. Their published works detail the development of a SkilMate finger, hand, and a pneumatic actuation and control system. Starting with the SkilMate finger and hand, the goal of the project was to create a mechanism that would improve task efficiency. To support the development of the system, the project team used information gathered from an interview with an unnamed astronaut about the utilization of his hands during an EVA[46]. The astronaut stated that during a task he is more likely to use his thumb, index, and middle fingers rather than the ring and pinky. This is to retain their functionality for tasks that require their use such as actuating the push-button on the safety tether. The project began with developing a mechanism for the metacarpophalaneal joint of the index finger which was then mimicked for the middle finger and thumb. The actuators chosen for this undertaking are ultrasonic piezoelectric motors which require low power, have few moving parts, and produce one of the highest torque-to-weight ratios of any actuator. The addition of vibrotactile displays inside the gloves at the fingertips further enhances the wearer's ability to determine if they have a firm grip on an object. Pressure sensors made of a conductive rubber were embedded in the fingertips and provide the necessary electrical signals for the logic controlling the activation of the vibro-tactile displays. The control logic measures strain in the conductive rubber rather than stress and the rubber was chosen for its ability to retain the necessary properties in low temperature environments[47]. The implementation of a pneumatic system was investigated to take advantage of the inherent

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[46] Yamada

[47] Yamada

force absorption of a pneumatic cylinder[48]. The prototype, shown in Fig 14, is controlled via a self-tuning PID controller. PID stands for proportional-integral-derivative and it is a feedback control algorithm that calculates the error between a process variable and a set reference value and attempts to minimize is thus driving the variable toward the desired value. Implementing this system in low pressure and variable thermal environments raises a few concerns regarding the safety of the crew member operating it. When pressurized the feed lines may become rigid and could impede the movement of the astronaut. The variable temperature will cause the tank compressed gas to fluctuate in internal pressure if not thermally isolated which can cause inconsistent operating characteristics.

Figure 14. Pneumatic actuators and SkilMate mechanism attached to an insulated glove to simulate the limited mobility of an EVA glove [Yamada].

The last prototype looked at was a glove with a power assisted metacarpalphalangeal, MCP, joint developed by ILC Dover and the Space Systems Lab at the University of Maryland in response to a NASA research announcement[49][50]. Unlike the prototypes discussed previously, this concept involved the fabrication of a glove whose neutral position was a closed hand rather than an open one. The prototype uses an actuation system to pull open the fingers rather than pushing or pulling them closed which

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[48] Li, D., Yamada, Y., Morizono, T., Umetani, Y., Yoshida, T., Aoki, S., “Design of Pneumatic Drive and Its Control System for a SKilMate Hand,” Proceeding of the 6th International Symposium on Artificial Intelligence and Robotics & Automation in Space, 2001.

[49] Lingo, R.. Cadogan, D., Sanner, R., Sorenson, B., “NASA Research Announcement Phase II Final Report for the Development of a Power Assisted Space Suit Glove.” NASA CR-97, 24 Dec. 1997.

[50] Cadogan, D., Lingo, B., “NASA Research Announcement Phase I Report and Phase II Proposal for the Development of a Power Assisted Space Suit Glove,” ILC Dover Inc. 30 October 1996.

circumvents the issue of force delivery described in the feasibility studies done by Favetto. Fig. 15 shows the actuation system which consists of a brushless DC servomotor with rotary encoder mounted on the dorsal side of the hand external to the bladder. The cable that opens the MCP joint spools around the shaft of the motor without overlapping ensuring a constant relation between motor torque and cable tension. The feedback required for the control loop to maintain tension in the cable is provided by tracking the degree of rotation the motor has gone through via the rotary encoder thus it is key to the success of the system that the cable does not spool over itself. To accommodate the extra material needed during flexion a rolling convolute is added to the MCP joint. The system was tested at ILC Dover, NASA JSC, and NASA Headquarters with subjects consistently reporting it offered a dramatic improvement to the MCP range of motion and torque required for movement[51].

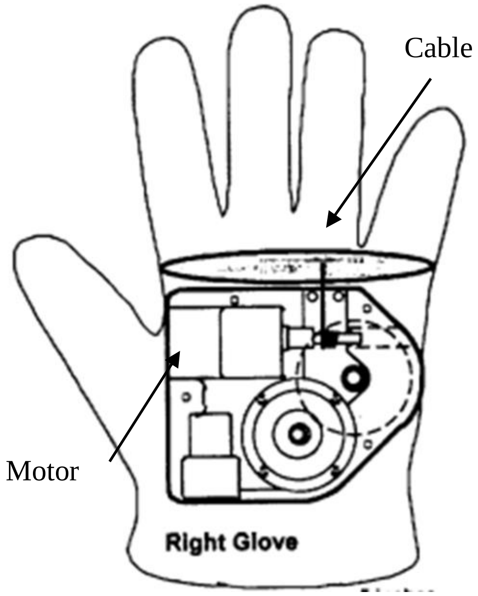

Figure 15. Powered metacarpal joint mechanism, cutaway image shows the motor and cable loop that pulls open the joint [Lingo].

Related Applications in Technology

As stated previously, part of the reason for the rise in interest in EVA glove robotics is due to the evolution of technology in recent years. Hardware is constantly getting smaller

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[51] Cadogan, D., Lingo, B., "NASA Research Announcement Phase I Report and Phase II Proposal for the Development of a Power Assisted Space Suit Glove," ILC Dover Inc. 30 October 1996.

making it possible develop a capable exoskeleton robot for the cramped environment of a spacesuit glove. Thus research into applications of robotics pertaining to mimicking or assisting the movement of the hand can provide a measure of current capabilities and introduce concepts that could aid in the development of a prototype system. The fields investigated included academic and hobbyist robotics, medical rehabilitation devices, advanced prosthetics, virtual reality, and tele-robotic systems.

Tele-robotics, or telepresence robotics, are robotic systems in which a person controls a mechanical system through some remote fashion. The German company Festo Corporate and the Japanese company ITK have developed two such systems. The Fest ExoHand, shown in Fig. 16, is a robotic hand-arm system that mimics the movements of the person controlling it[52]. The user wears a glove embedded with sensors and accelerometers that gather position data on the hand and fingers. This data is processed and used to control the electric motors used for positioning the hand and the pneumatic cylinders controlling finger articulation. The control glove is also capable of sensory feedback using the pneumatic actuators attached to it. Pressure sensors in the robot hand detect when an object

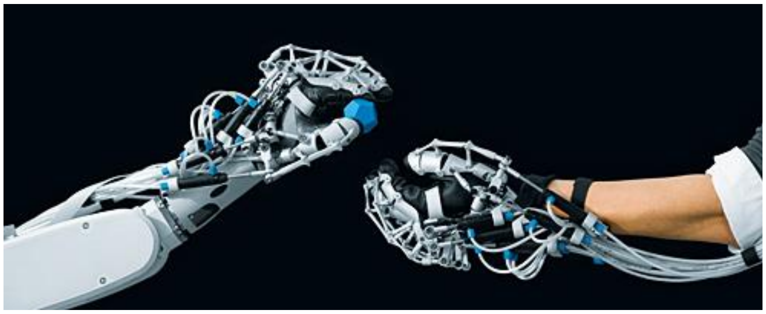

Figure 16. Image of the ExoHand system designed and developed by Festo showing the control glove and robotic appendage[ExoHand].

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[52] "ExoHand Human-Machine Cooperation," Festo AG & Co. KG. Esslingen, Germany. April 2012, <http://www.festo.com/net/SupportPortal/Files/156734/Brosch_FC_ExoHand_EN_lo_L.pdf> accessed June 2014.

is grasped. This information is relayed to the control hardware which, in turn, activates the appropriate cylinders and creates a variable resistance to motion.

The ITK Handroid, like the Fest ExoHand, is a telepresence robotic system using a control glove to manipulate a robot appendage[53]. It takes a simplified approach using a single electric motor, cable driven actuation system per digit. Furthermore the hand itself resides on a pedestal and does not move. However, its sturdy design, rapid response time and accurate mimicry of the user's movement make it well suited for its intended use in environments that are inaccessible or too dangerous for the human hand. The control glove uses flex sensors which are resistors whose resistance value changes as the component deforms. The degree to which the robotic hand closes each digit corresponds directly to the observed value of the flex sensor and the control logic is able to interpret fairly accurately the finger flexion of the user and duplicate it with the robot. One major difference that the Handroid has from the ExoHand is a lack of force feedback in the control glove meaning the user does not receive any tactile indication of a secure grip.

Shifting focus to the field of advanced prosthetics, the latest advancement toward the creation of a cybernetic limb comes from the Prosthetics Division at the multinational company RSLSteeper[54]. Dubbed the "world's most advanced prosthetic hand" by its creators, the bebionic3 demonstrates what robotic replication of t he human hand can look and perform like. Shown in Fig. 17, it is able to reproduce nearly all of the degrees of freedom of a healthy hand in a compact form factor. It has 14 different types of programmable grips that enable a person to complete daily activities from holding bags to

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[53] "Handroid Multifingered Robot Hands," ITK Co. 2011, < http://www.itk-pro.com/en/pro/kindengisyu.htm> accessed June 2104.

[54] "Bebionic3," RSLSteeper Prosthetics Division. Hunslet Trading Estate, Leeds, Yorkshire, UK,< http://bebionic.com/the_hand> accessed June 2014.

typing and clicking a mouse. The hand weighs just over one pound and uses electromechanical actuators situated in the hand to drive the fingers. The maximum force output varies with each grip type, but the device is capable of generating 140 N or 31lbs of grip force and holding a static load of up to 45kg or just under 100lbs. The key attribute to notice with this prosthetic is its compact size. The entire prosthetic is a hand/forearm assembly the size of an average human's and is almost as articulate. It illustrates how capable and compact a robotic system can be.

Figure 17. Image of the bebionic3 hand developed by RSLSteeper with the linkages for the motors that drive the fingers visible [Bebionic3].

Medical rehabilitation robotics is primarily associated with therapeutic devices meant to treat ligaments or digits that have lost strength or nerve control due to stroke or injury. Though there are a number of examples to select from the devices discussed below were specifically designed to manipulate the fingers of the hand and each demonstrate different approaches to force delivery. The size of the devices is not necessarily conducive to the EVA glove application but that is because the components do not have to fit within a specified envelope. However they illustrate the basic mechanics needed to achieve the desired function and place into perspective the challenge of minimizing the hardware profile.

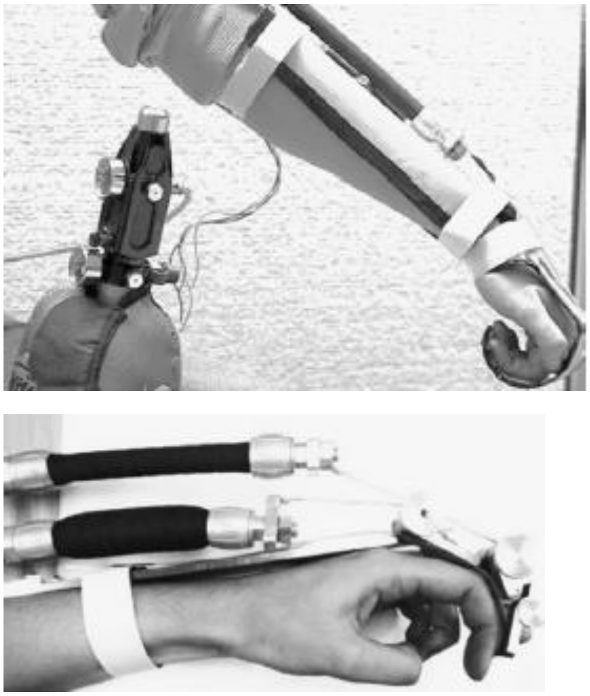

Figure 18. Prototype I (top) and II (bottom) of the rehabilitation devices driven by compressed air and pneumatic muscles developed by Matheson [Matheson].

In an experiment conducted by the Australian Centre for Field Robotics two designs were conceived and developed for light weight, low profile devices to facilitate the flexion of fingers that have lost strength or nerve control[55]. Pictured in Fig. 18 each device utilized pneumatic muscle actuators to provide the flexion force and pressure sensors to detect the user's intent. Prototype I was designed to aid in the grasping motion of the hand while Prototype II actuates a single finger. The designs were relatively light weight, hovering around 2 kg each, however they were not that low profile. The pneumatic muscles offer a high strength to weight ratio however, that value is dependent on the cross sectional area of the "muscle" and the pressure of the fluid pumped into it. This is because the contracting force is generated by pressurizing a flexible segment of material labeled the "muscle" with gas or fluid causing the long axis to shorten and the short axis to bulge out. The larger the cross section the more fluid can be pumped in without compromising the material because there is more surface area for the fluid to push on keeping the stress on the skin below the yield of the material. Thus a trade occurs between maximizing force and minimizing size which

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[55] Matheson, E., Brooker, G., "Assistive Rehabilitation Robotic Glove," Australian Centre for field Robotics, University of Sydney, NSW Australia 2006.

ultimately yields a system with larger components. Interestingly, the same work was republished in 2012 under the title *Augmented Robotic Device for EVA Hand Manoeuvers*[56] indicating the developers feel it is an applicable technique for assisting in EVA activities. Another example comes from Australia as well and was specifically developed for the rehabilitation of hand muscles following a stroke[57]. Shown in Fig. 19 the device uses linear electromechanical actuators to exert a push/pull force on a system of rods and joints that put the fingers through the full range of flexion and extension. The system has 15 degrees of freedom and is controlled using a separate glove inlaid with flex sensors that is worn on the individual's healthy hand. As stated earlier, flex sensors change resistance based on the degree to which they are bent, this value is then translated into positional knowledge and the linear actuators respond accordingly. The design of the device is rather high profile and bulky which, as with the devices created by Matheson, is a product of its mechanics. As demonstrated by the prototype developed at the University of Maryland, pulling the fingers open in extension

Figure 19. Stroke rehabilitation system that utilizes a mechanized glove (left) and a control glove (right) that are placed on the impaired and healthy hands respectively [Rahman].

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[56] Matheson, E., Brooker, G., "Augmented Robotic Device for EVA Hand Manoeuvres," Australian Centre for field Robotics, University of Sydney, Acta Astronautica 81, 2012 pp. 51-61.

[57] Rahman, A., Al-Jumaily, A., "Development of a Hand Exoskeleton for Rehabilitation Following Stroke," International Symposium on Robotics and Intelligent Sensors. Procedia Engineering 41, 2012, pp. 1028-1034.

can be done with a small device. However, as mentioned in the studies by Favetto, attempting to push them closed requires a system of pushrods that can deliver force to the desired location. The pushrod system used in by Rahman et al illustrates this point clearly due to the height required by the system to deliver the desired function.

Figure 20. Image of an anatomically inspired robotic hand design with the 'tendons' that drive the movement of the index finger visible [Van der Smagt].

The next area of consideration is the academic and hobbyist robotics field which provides a wide variety of concepts and prototypes that don't always have a professional application but are driven by creativity and inspiration. In a study released by the Institute of Robotics and Mechatronics at the German Aerospace Center DLR the authors provide a look at internal efforts to construct robotic systems whose movement characteristics are inspired by those of humans[58]. They provide summaries of relevant technologies including their humanoid robotic hand, shown in Fig. 20, whose structure replicates the human skeleton, movement characteristics and force levels are comparable to its biologic counterpart, and a bio-inspired touch sensor system to provide environmental feedback. Furthermore, the robot hand can act as an exoskeleton, demonstrating the ability to be attached to a person's hand to provide muscle and nerve rehabilitation. At the Kawabuchi Mechanical Engineering Laboratory in Japan design and development of advanced robotic and exoskeleton hands is an ongoing field of research to pursue the harmonious integration of

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[58] Van der Smagt, P., Grebenstein, M., Urbanek, H., Fligge, N., Strohmayr, M., Stillfried, G., Parrish, J., Gustus, A., "Robotics of Human Movements," Journal of Physiology – Paris 103, 2009, pp. 119-132.

man and machine. In a paper released in 2007 the latest iterations of their endoskeleton and exoskeleton designs were detailed[59]. The endoskeleton focused on creating a robotic hand that was similar in size and weight to the human hand while maintaining as much functionality as possible, two goals which generally oppose each other due to the characteristics of mechanical components. The kinematics of the robot reflects the human hand and the motors controlling the actuation of each joint are contained within the silhouette of the hand itself. Overall the robot hand exhibits extraordinary functionality for its size, successfully demonstrating the ability to shake hands, grip pens and pinch business cards. The one caveat to this is that the system is very low power due to the small size of the components used resulting in a practical payload of about 1kg at the wrist joint making it suited only for delicate operations in its current form. The exoskeleton counterpart was created to fulfill a role identical to that of the Festo ExoHand system. The wearer would be able to move within the exoskeleton and remotely control the robotic endoskeleton. The robot would in turn provide feedback via the pressure sensors in its fingers signaling to the control software when an object had been successfully grasped. The motors in the exoskeleton would then provide a resistive force and the vibro-tactile displays in the fingertips would generate a tactile sensation. One of the challenges met was creating a mechanical joint that could move in a similar fashion to those which reside in the phalanges of the hand. As will be elaborated earlier in the feasibility studies, the interphalangeal joints do not behave as classic hinge joints. This was addressed with the addition of a sliding gear system[60]. The exoskeleton hand is able to accommodate full range of motion of the digits

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[59] Kawabuchi, I., “A Designing of Humanoid Robotic Hands in Endo and Exoskeleton Styles,” Advanced Robotic Systems International. Kawabuchi Mechanical Engineering Laboratory, Inc. Japan, 2007.i

[60] Kawabuchi, I., “A Designing of Humanoid Robotic Hands in Endo and Exoskeleton Styles,” Advanced Robotic Systems International. Kawabuchi Mechanical Engineering Laboratory, Inc. Japan, 2007.

except for the pinky which was excluded due to its lack of involvement in general activities. The mechanism for the thumb demonstrated slight inconsistences when interpreting the intent of the user and a more advanced control algorithm is undergoing development at the University of Tokyo to correct this[61].

The last area of related technology discussed in this paper is that of virtual reality and motion capture. Generally advancements in this realm come out of the private and commercial sector meaning the developers are either driven by delivering the most functionality at a specific price point for a target market or creating the most capable system they can for personal use. One of the most accomplished implementations of this category of technology belongs to the company Cyber Glove Systems[62]. Shown in Fig 21 the company has developed a multitude of sensor laden gloves that are able to detect movement with high fidelity. The software that comes with the glove interprets these signal outputs and can replicate the user's hand movements with a virtual hand to remarkable accuracy. The sensors used are a proprietary flex sensor technology which is sewn onto the gloves at each joint in specific orientations

Figure 21. Images of CyberGlove's products which include a standard sensor glove (left), a tactile feedback model (top-right), and a force feedback model (bottom-right) [CyberGlove].

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[61] Kawabuchi, I.

[62] CyberGlove Systems LLC, 2010. < http://www.cyberglovesystems.com/> accessed May 2014.

giving it the ability to capture every degree of freedom[63]. The more advanced models have accelerometers and electric motors that provide special tracking data and force feedback for the user respectively.

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[63] CyberGlove Systems LLC, 2010. < http://www.cyberglovesystems.com/> accessed May 2014.

CHAPTER III

METHODOLOGY

The methodology used to design and develop the prototype movement assistance system utilizes that of the engineering design process with human-in-the-loop testing. Before the design process may begin the requirements of the system are listed and the drivers of the design are identified. Next the desirable techniques and technologies found in the research detailed in the previous section are noted. Simultaneously the previous prototypes are used to identify the subsystems in this category of device. The aforementioned requirements will then be flowed down to the identified subsystems to better define their roles and the performance that is demanded of them. As the initial design is created these performance requirements will aid in determining viable methods and architectures for each subsystem which will lead into the design of the system as a whole. Additionally what is occurring during this phase of the project is the development of trade studies where potential architectures, methods and components for each of the subsystems are compared and contrasted to determine which option appears to present the best solution.

The design process is iterative in nature, thus it requires an initial input. The initial design is generated based on previous prototypes as stated earlier though it is not characteristic of the final product. This starting point will be used to test the function of the system as a whole and determine in what areas the performance requirements are not being met. The testing that is done may be both conceptual and physical depending on the system component in question. Many of the higher level requirements, such as size or mass restrictions, may be adequately investigated through calculation only however unquantifiable characteristics such as ergonomics require component development and user feedback. Thus the human-in-the-loop testing factors in during the various stages of development to direct the design just as trade studies do. With each iteration the design will close in on a viable prototype that satisfies the goals outlined at the beginning of the project.

One concept that must be kept in mind is that there can be numerous solutions to a particular engineering problem and one should only switch to a new architecture is the current one lacks the ability to meet requirements at a fundamental level. During this project an initial architecture was chosen and carried through the design process and changes were made at the system level only when the current architecture lacked capability. The time frame for this project is also kept in mind thus it was deemed better to fully develop out an architecture and note any shortcomings because it is easy to become stuck in the design process for a particularly long period of time. Another note of mention is that though the research conducted was extensive it is by no means exhaustive. There remains the possibility of previous works left undiscovered or additional papers published during the creation of this document. Should further development of this concept be done it is advised that research be continued to discover any new information.

CHAPTER IV

PROJECT DEVELOPMENT

System Requirements

As stated in the Methodology, the development of this project began by defining the requirements and drivers for this system. It was stated that the objectives of this undertaking were to enhance the abilities of the hand without interfering with its function or natural range of motion. By breaking this statement down, the requirements that flow out of it are to develop a system that shall increase the capability of the user, it shall not utilize components or techniques that restrict or inhibit natural movement patterns, and should be as ergonomic as the design will allow. Ideally, the system will be able to mimic the underlying anatomy without creating a device that is bulky and obtrusive. The drivers of the design may also be derived from these statements. The desire to maintain a light, low-profile design will have significant influence on the evolution of the design and thus may be selected as the first driver. The second driver may be derived from the requirement of performance. One of the best ways to guarantee system performance is maintaining a simple and robust architecture that fulfills expectations. Thus, the system architecture will employ simple, well understood technologies which deliver the performance desired. It is understood that during the design process requirements may be shuffled, changed, or removed and such occurrences are only warranted if supported by substantial evidence. A design characteristic that stems off of the second system driver is the decision to develop a system that would only assist three digits rather than all five. Prior to the design process it was established that the prototype’s functionality may be sufficiently tested using only a subset of phalanges. It was decided that the thumb, index, and middle fingers were to be selected due to their primary roles in grasping actions. However, as will be detailed in the text, this was modified replacing the thumb with the ring finger.

Subsystem Identification and the Initial Concept

With the project objectives clearly stated, the research conducted on the previously developed prototypes is studied to determine advantages and drawbacks of various approach as well as concepts or techniques applicable to the objectives of this project. What is noted is that each system falls under one of two categories, pull or push action. Pull action uses one or more actuators to pull the hand open or closed. The K-Glove developed by NASA and GM uses cables which run along the pulp of the digits to pull them closed whereas the powered glove developed at the Space Systems Lab at the University of Maryland uses a dorsal mounted cable to pull the metacarpal joint open. The advantage with the latter is that there are no components mounted on the palmar side of the hand so risk of further hindering tactility is negated. However with the former, tooling for glove manufacturing would not have to be redone. As detailed in the Literature Review in order for the approach selected by the University of Maryland to function properly the bladder of the glove had to be recast into a closed grip rather than a neutral position. During operation the motor would pull open the fingers of the glove when instructed to by the control system hardware.

Push action systems use actuating mechanisms to apply a force to the dorsal side of the fingers and push them into flexion. Taking the Festo Exohand as an example, the relatively large structural components it features transfer the force from the pneumatic cylinders to the phalanges of the user. Another example of this architecture is illustrated in the SkilMate hand which also uses pneumatic actuators to push joints into flexion. Common traits between these two examples are their large structural components required to transmit force from the actuators to the desired location. Intuitively this makes sense because this approach requires moments to be generated about the desired joints thus requiring the presents of a moment arm. Compared to the pull action systems they tend to be cumbersome. This is because a torque may be placed on the joint without the use of a moment arm, a technique which is employed by the musculoskeletal system. Thus it behooves the design of this prototype that a pull action system is chosen for the initial concept.

With the cable driven approach offering an attractive starting point the next characteristic that was looked at where the actuators of these systems. While the type of actuator tended to vary, electro-mechanical and pneumatic were the most common, for the most part each system utilized linear actuation. Intuitively this makes sense as the flexion and extension of the fingers occurs in one plane. A characteristic that is well known and has been utilized extensively to replicate phalangeal motion by puppeteers and animatronics experts. The decision to use a specific type of actuator is influenced by several factors and the complete process is described in the following section, along with a corresponding trade study, however components which generate linear motion without additional hardware propose a simple and succinct approach for the system.

What begins to fall out of this process is the definition of the subsystems that allow these prototypes to function as a complete unit. The actuator and force delivery method may be thought of as the core of each design, distributing the forces generated in a manner that most benefits the end user, and the hardware required to complete the system support this purpose. Thus the subsystems that were identified include the actuators, control logic that governs the behavior of the actuators, sensors that initiate movement, system power, and the structural components associated with delivering the force from the actuators. Each of these subsystems brings their own requirements stemming from the hardware chosen to fulfill their roles, and these will be reflected in the evolution of the system as a whole. With the subsystems identified and desirable characteristics of previous designs noted the next phase is to kick start the design process by creating an initial concept and apply systems engineering principles to identify areas of improvement and work toward the final architecture.

System Development

During the initial phases of development time was spent experimenting with hardware that was readily available while the design process began its first iteration. The Arduino Uno microcontroller was already procured from a previous project and deemed acceptable as the platform for developing the control architecture given its robust nature. Familiarity with the board's capabilities, inputs and outputs, and coding language had to be established prior to the completion of the first design iteration. Thus three days were spent learning the coding environment, script language, and necessary commands. From this it was discovered the diversity of hardware that could be utilized with this platform. The board was capable of receiving digital and analogue signals and could output a steady voltage signal or a modulated frequency that is commonly used for positional control with servo motors. As the comfort level with the hardware grew, the development of a control architecture was pieced together. Building on the simple idea of utilizing an input signal to trigger the movement of a motor, a script was written that would turn an LED on/off in response to an input signal. This evolved into a script that utilized the modulated outputs and a variable resistor to dim the LED. As the variable resistor was adjusted, the change in resistance was mapped to a frequency value which was sent to an output terminal and caused the LED to blink at the specified frequency. This is called pulse-width modulation, or PWM, and is commonly used as the control signal for servo motors with the added step of mapping the frequency to a positional value recognized by the motor's rotary encoder. The scripts for these operations may be viewed in the Appendices. At this point competency with the Arduino had been established and efforts were shifted toward developing the other subsystems to complete the initial design. Trade studies were performed to determine which options offered the most desirable characteristics for each subsystem. The studies themselves may be seen in Table 1.

Due to technologic advancements and the continually increasing "tinkering" culture there were a number of actuator types to choose from. DC motors tend to be the simplest mechanisms to integrate into a system due to their "on/off" nature when power is supplied to them. However, they tend to favor continuous use and the amount of distance traveled by a finger during flexion and extension is not significant enough to warrant this component. Furthermore the rapid directional changes that could occur during the operation of the assistance system are better facilitated by servo-style motors which are design specifically to handle such tasks.

Table 1. Subsystem options with along with their key characteristics.

Actuators						
Servo	**DC Motor**	**Stepper**	**Solenoid**	**Pneumatic**	**Linear**	**Piezoelectric**
Uses electricity Variety of sizes, torque outputs, and gearing ratios Positional knowledge Directional control, can be stepped Popular in hobbyist robotics	Uses Electricity Used for drive trains, activates when power is supplied High power to weight ratio	Uses Electricity Hybrid of DC and servo motors High rpm and positional accuracy Relatively low torque Commonly used in CNC machines	Uses Electricity Linear “on/off” actuators, use magnets to achieve positional state Weak initial force, builds as it moves through the electromagnetic coil Good for latching mechanisms	Uses compressed gas to generate mechanical motion Simple, reliable Thermal variations affect compressibility of gas High pressure gas is a potential hazard	Uses DC or servo motor and lead screw to create linear motion Positional knowledge is possible High torque to weight ratio Gearing allows high holding torque	Uses electricity to create a standing wave that pushes a rotor High positional accuracy High torque to mass ratio Wide range of sizes Used in precision lab equipment

Structural Components/Force Delivery Architecture	
Cable System	**Hard Components/Exoskeleton**
Minimal structural components, uses anatomy of wearer Offers slim and sleek delivery of force and diverse architecture	Rugged yet bulky, lends itself to the classic exoskeleton image Improper design can limit natural range of motion, joint design is crucial for ergonomics

Sensors		
Variable Resistors	**Electrodes (EMG)**	**Momentary Switch**
Electronics components whose resistances are able to be changed in a linear or logarithmic fashion Variety of types Simple, reliable, easy to implement	Sense electrical signals sent to muscle groups via nervous system Requires additional equipment and software for signal processing Calibration required to distinguish signals from different muscles	Simple and robust, used in basic circuits, easy to implement Wide variety of switch types No signal processing required, discrete “on/off” states

Pneumatic actuators, though used in a few of the prototypes discussed previously, were deemed hazardous to the individual operating in a vacuum due to their dependence on pressurized air. Piezoelectric motors do offer an attractive option because of their small size and high torque outputs however, they are not as easily integrated into the Arduino board as servos. Furthermore, servo motors are widely available thus making them, specifically linear servos, a reasonable starting point for this subsystem. As hinted at in the previous subsection, pull action systems that utilize cables for force transfer offer the best solution due to their low profile and minimal structural components required for operation. For the sensor selection, the use of momentary switches or variable resistors facilitates the creation of a simpler system as EMG electrodes required additional hardware to interface with as well as code for signal processing. Though they offer the potential to translate commands sent from the brain to the assistance system's actuators, the additional complexity far outweighs it for this project. Momentary switches allow the creation of simple circuit logic using on/off states to trigger actuator movement however, variable resistors could allow a more intuitive interface for command input. As discussed previously the company CyberGlove demonstrated that the use of variable resistors, specifically flex sensors, allows signal data related to finger movement to be easily obtained and interpreted. As the component is flexed or bent its electrical resistance decreases, this fluctuation can be measured and mapped to positional commands for the actuator. After weighing each option it was decided that variable resistors would serve as the sensing mechanism, linear servos would be the actuators, and cables would serve to deliver the force of the actuators. The flex sensors have a resistance value ranging from 25kΩ to 100kΩ depending on the degree to which they are deformed and are rated for over one million bend cycles[64]. The linear actuators selected are Firgelli L12-R motors[65] and were chosen because their characteristics offered a middle ground between the available options. The stroke length of the lead screw is 50 mm, the gearing ratio is 100:1 which allows a balance between movement speed and power output. The resistance produced by the specific garment used for this experiment was never quantified, however it was postulated to be under 5 lbf or 22 N. The force produced by the 100:1 gear ratio during movement is 23N and it had a static holding force of 80N which was deemed satisfactory for this project. Due to the fact that a rule-of-thumb had not been established for actuator speed the 6 mm/s offered by this gear ratio was deemed sufficient.

The power requirements for this system remained relatively low, allowing the Arduino board and proposed three motors to be driven off of a USB power cable connected to a laptop. An external power pack for the system was acquired however the current draw from the motors turned out to exceed the rated output of the battery and caused a brown out of the circuit board. After a time it was deemed acceptable to keep the system tethered to a laptop computer as the power source. The reasoning behind this decision is it allows rapid adjustments to me made to the code controlling the behavior of the motors during testing, a valuable ability for project development.

With the initial component selection completed, the development of each subsystem commenced. Much of the software development to control the actuators had been accomplished during the initial experimentation with the board thus a majority of the

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[64] "Flex Sensor, Special Edition Length," Spectra Symbol, Data Sheet, http://www.adafruit.com/datasheets/SpectraFlex2inch.pdf.
[65] "Miniature Linear Motion Series- L12," Firgelli Technologies Inc., http://www.firgelli.com/pdf/L12_datasheet.pdf.

time during this iteration of the design centered on the dynamic of efficiently delivering the force from the linear actuators to the joints of the fingers. It should be noted that the stroke length of the motors is adjustable through the Arduino coding environment, however it was found that the default length of 50 mm was sufficient. The circuitry for the system that was created is displayed in Fig. 22 and noteworthy features are the signal wires which are used to measure the voltage of the node between the variable and standard resistors. The reason this works is because electrical loads placed in series draw the same current from the power source but divide the voltage. As the flex sensor’s resistance changes the voltage drop

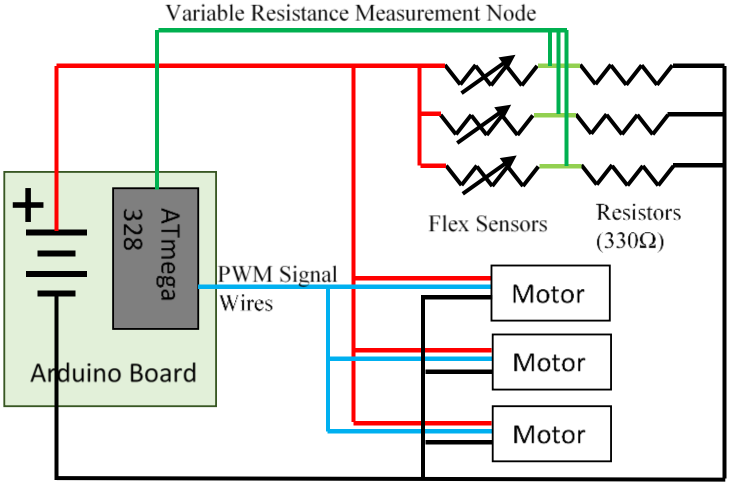

Figure 22. Circuit diagram for variable resistor architecture.

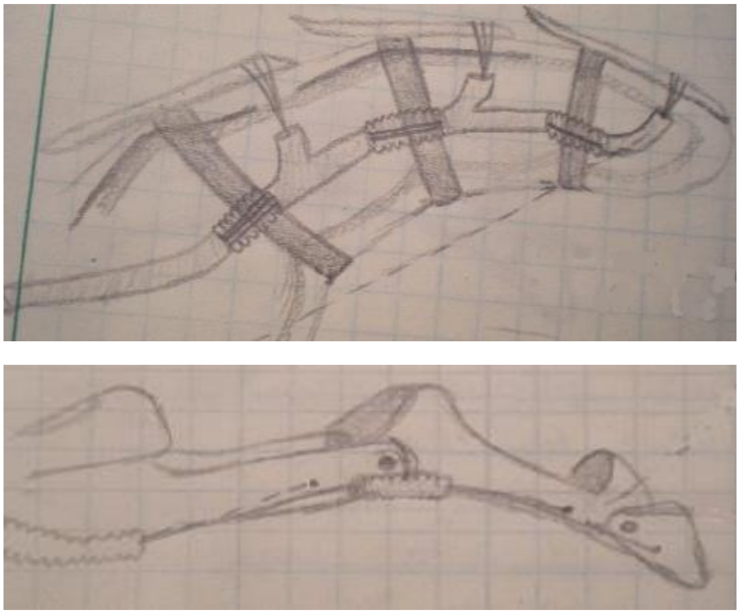

Figure 23. Illustrations of two initial concepts for structural components utilized to transmit force from the actuators to the fingers.

across it changes with respect to that of the resistor placed in series creating a measurable data point that, in this case, is used to initiate actuator movement.

The flex sensors, linear actuators, and cabling were acquired prior to the completion of the design for the components that would secure and route the cables around the hand. A diagram of two initial concepts may be seen in Fig 23. However, this benefited the overall progress of the design as the cable purchased was larger and less flexible than previously estimated, presenting issues with the intricate components designed. The designs of the components were adjusted accordingly however manufacture could not commence. The Makerbot Replicator 2, 3D printer that was to be the primary means of prototyping components was not functioning at the time. Though printer would be repaired soon after this point, the time prior to its repair was spent testing the proposed cable routing concept with components fashioned from additional materials. This experimentation uncovered a flaw with the current approach. Mounting the cable to the side of the finger as shown in Fig. 24 created an ergonomic issue as the components would make the finger too large to function properly with its neighboring digits. Rather than letting the fingers move in a natural way it would force them to splay outward creating an uncomfortable experience during flexion. The component design continued to evolve in an attempt to

Figure 24. Images of the initial techniques used to route cables along the dorsal side of the hand.

mitigate this issue however the natural space between digits remained too slim to accommodate additional hardware. Furthermore, experimentation showed that when the actuator would place tension on the cables the interphalangeal joints would flex but the metacarpal would extend. This was because the cable was being pulled on the dorsal side of the joint rather than the palmar thus creating a moment in the opposite direction. To resolve this the cable would have to pass on the palmar side of the metacarpal joint which would require additional hardware further increasing the already bulky nature of the system. This was decided to be undesirable and would be addressed in the next iteration. Issues were also being encountered with the flex sensors accurately detecting movement due to sensor degradation and signal noise. As seen in Fig. 25 the sensor was attached to a common work glove near the interphalangeal joints of the index finger, a single digit was selected for expediting testing. The sensor was sewn to the glove to ensure it would properly reflect the deformation in the digit. To establish the bounds on the values received from the component during flexion a script was written for the microcontroller that would record the highest and lowest values obtained as the sensor was deformed and flattened during the first five seconds it was powered on. This technique initially yielded promising results however, through continued experimentation

Figure 25. Image of the flex sensors sewn to the exterior of a glove to demonstrate the proposed movement sensing concept.

it was noted that consistent performance was difficult to acquire. The control software would successfully calibrate the sensor and map the values to the position of the actuator's lead screw, but after a relatively short number of cycles the sensor appeared to stop conducting electricity. This was later verified by looking at the voltage reading across the components leads and again by monitoring changes in resistance through the Arduino software. Operating under the assumption that the component was a slip in quality control it was replaced with another and the occurrence repeated itself. An investigation was not performed to determine if the batch of sensors received was bad or if this was a product of the company the components were purchased from. However, as previously noted the maximum number of cycles reported by the manufacturer is orders of magnitude greater than those displayed by the ones acquired for this project[66]. The second issue encountered was the signal noise and the amount of post-processing that had to be done to sufficiently mitigate it. Due to the fact that the wires used for this project were not shielded and several of the electronics components were placed in close proximity to one another it is reasonable to assert that the analogue signal being read from the flex sensors acquired background noise. To cope with this a high-pass filter and moving average logic loop were implemented. This greatly increased the signal to noise ratio and provided a smooth experience during actuator recruitment. Yet, the additional processing required created a noticeable lag between the times an individual would bend the sensor and the actuator would move. Even during slow, controlled flexion of the finger the lag would hinder an individual's ability to perform useful tasks. For these reasons, it was decided to forgo the use of a variable resistor in favor of a more robust solution.

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[66] "Flex Sensor, Special Edition Length," Spectra Symbol, Data Sheet

The next iteration of the design was commenced with the goal of addressing the aforementioned issues with the flex sensors and cable routing beginning with the latter. It was decided that the optimal method to consistently pull the fingers closed would involve routing the cables along the pulp of the fingers and across the palm area. One risk associated with this approach is the possibility of reducing the individual's tactility and interfering with their ability to accomplish tasks. During testing it would be found that the postulated hindrance of the cables would be negligible as other factors held greater sway over the performance and ergonomics of the system. One issue which did arise was the cables "bowstringing" or pulling away from the surface of the fingers as they were flexed. To address this small tubes were manufactured and attached to the proximal phalanx of each digit via Kapton tape. At this time the viability of assisting the thumb through its range of motions was brought into question as it would require multiple motors and an increasingly complex cable scheme involving running a cable horizontally across the palm to facilitate opposition. Though this would bring increased functionality, the time required to design and test a system with this added complexity would exceed that which was available. Thus it was decided to exchange the thumb for the ring finger maintaining the three-digit architecture, a change that will be taken into account when assessing the results of the experiments. With these issues addressed attention was turned to that of the flex sensor components.

Returning to the subsystem trades the decision was clear, momentary switches were the only option that would provide a robust solution without adding layers of complexity to the system. Momentary switches, unlike flex sensors, have two discrete states, "on" and "off." This negates the need for resource heavy signal processing code producing a faster

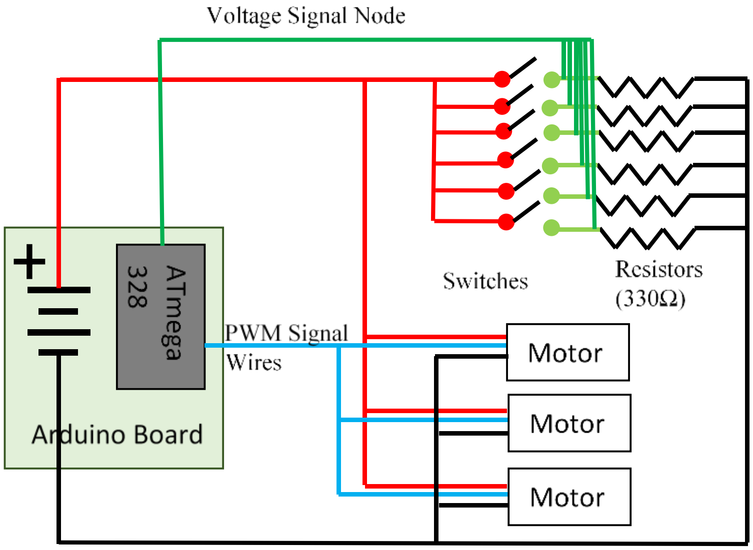

Figure 26. Circuit diagram of architecture utilizing momentary switches to recruit motor actuation.

experience with the Arduino. One shortcoming that was addressed regarded the directional control of directional control for the actuators. With the variable resistors the motor position replicated the movement of the finger because position values were mapped to specific voltage readings. With a switch there is an "on" state to tell the motor to move but the direction is not selected. To solve this a two-switch system, the circuitry of which may be seen in Fig. 26, was implemented. One switch would command the actuator to extend and the other to retract. Each time a switch is pressed the code would step the motor a specified distance in the corresponding direction, the step size itself can be adjusted to create a more ergonomic experience. A couple concepts for switch placement were drafted to understand the implications this new component had on the system as a whole. The first placed both inside the glove on the palmar and dorsal surface of the fingertip. To operate the system the user would flex or extend their distal phalanx and the buttons would cause the motors to follow suit. This creates a relatively self-contained system however the amount of space required to house two switches and the finger of the individual exceeded the finger diameter of the glove used during the test. Thus the concept that was implemented was the second, which

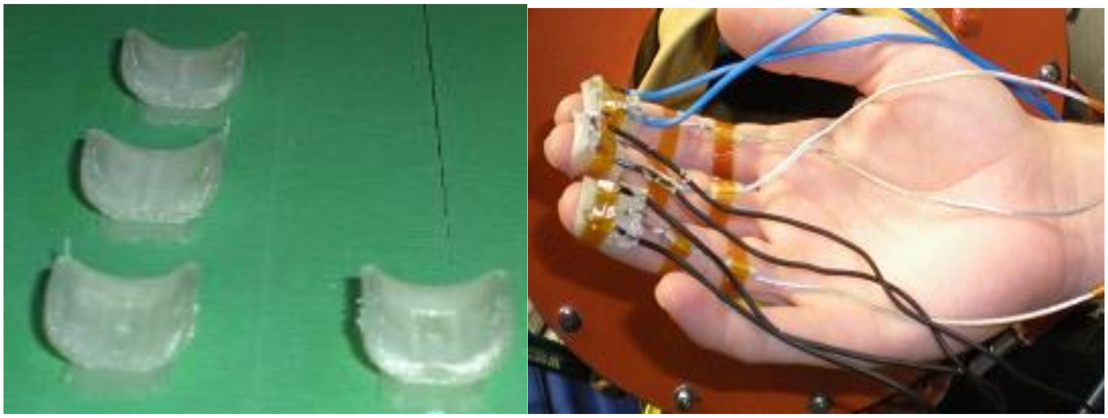

Figure 27. Images of the initial switch housing concept and how it is secured to the hand.

placed one switch inside the glove and the other on a control box outside. The user would activate the interior switch for flexion and the exterior switch for extension. The last component developed during this iteration of the design is the switch housing that will be used to hold the switches against the distal phalanxes of each finger. As shown in Fig. 27 the design mimics the contour of the pulp of the phalanx to help position the finger over the switch. The housing has a square socket which the switch is placed into and secured via a pressure fit. The leads of the switch are left exposed and soldered to the connecting wires which are in turn set into the corresponding pins on the circuit board. At this stage the system has made another complete iteration and is tested in ambient conditions and inside the garment that will be used to conduct the experiments described later in the text. The switch housings lack any direct means of attachment to the hand and thus are held on with Kapton tape as seen in Fig. 27. During the tests the system was found to meet performance expectations, it was able to successfully flex and extend the fingers when commanded in ambient conditions. However, when it was placed inside the glove box and a weak vacuum was pulled, the switch housings separated from the fingers and became wedged near the distal interphalangeal joint. A position which kept the momentary switch in the "on" condition causing the system to become unresponsive. The situation was remedied and the issue was noted. The performance of the other subsystems during this test satisfied their requirements and thus were deemed acceptable for the matured design. However, the dilemma with the design of the switch housing became the focus of the next iteration in the design process.

The first solution that was proposed involved creating a new bladder that would have the switch components and cable tubes molded into it, completely removing the hardware from the user's hand. However the casting agent did not set up properly and acquiring new material would exceed the allotted project time. Next, an attempt was made to attach the components to the interior of a prefabricated bladder with strong adhesive. The material of the bladder however prevented the adhesive from forming a bond with th e switch housings and tubes. It is now theorized that securing the components to the bladder as opposed to the hand would have improved the ergonomics of the system and possibly its performance due to the force from the motors being delivered directly to the glove. Further explanation is provided in the Results and Discussion section below.

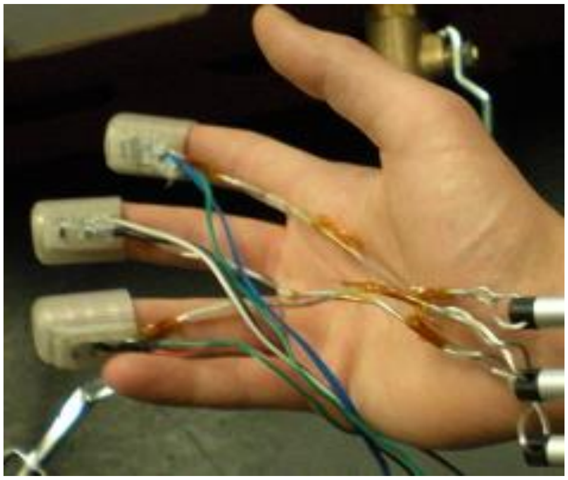

Figure 28. Image of the revised switch housing design, illustrating how it is attached to the hand.

With efforts to attach the components to the bladder proving unsuccessful, designing a switch housing that would enclose the distal phalanx was decided as the most viable option. The component had to be small enough to fit into the finger to the glove box garment while simultaneously allow the finger of the user to move freely inside of it to actuate the switch. The new design, shown in Fig. 28, integrated the switch socket from the previous generation onto a relatively large thimble structure. The switch was still pressure fit into place with the leads exposed so it may be wired to the microcontroller and the cable running from the actuators secures to the component as before. With the development of this component complete another test run was conducted in ambient conditions and inside the glove box. The system as a whole as well as each component functioned well, fulfilling design requirements and bringing the design to an acceptable level of maturity. At this time the development of the assistance system had concluded and focus was shifted to the development of an experiment, or experiments, that would assess how well the system performs and to what degree the original goals of the project were met.

Experiment Development

The experimental procedures to test the assistive system underwent several changes as tasks were attempted with the system and difficulties with certain types of activities were noted. Initially a “work bench” housing several different activity stations was designed and constructed. As seen in Fig. 29 the bench had two s tations that were separated by small handrails. A tether was attach to the left most handrail via a carabineer and the subject would be required to move the carabineer from one hand rail to the next as they completed each station. The stations consisted of a nut and bolt assembly and a lock collar platform. The nut and bolt assembly would be used to test the system’s ability to assist in finite motion such as that required to pick up and articulate a screw driver to tighten a bolt. The lock collar platform required the subject to move the female end of a valve assembly from one spout to another testing the system’s ability to flex the fingers in a controlled manner as the subject slides open the lock collar to detach it from and attach to the respective male ends. Additionally there was a hand exercise tool that was placed on the platform just in front of the work bench that would be used to assess the assistance system’s ability to increase the endurance of the test subject. The procedure developed for this test bed required the subject to first use a screw driver on the nut and bolt assembly to turn the bolt a specified number of times. Once completed the subject would then set the screwdriver down on the platform and remove the carabiner form the left handrail and secure it to the right one. Then the subject would arrive at the lock collar platform and transfer the female end of the valve from one spout to the other. After the lock collar has been successfully attached the subject would then pick up the hand exercise tool and squeeze it until muscle fatigue prevents them from doing so. During preliminary testing however, it was found that the small size of the chamber and lack of mobility in the w rist of the glove greatly interfered with the subject’s ability to complete the tasks. The orientation of the glove made it extremely difficult to pick up, grasp, and turn the screwdriver to complete the activity at the first station. Moving the caribiner was slightly easier due to the large size of the object but orienting

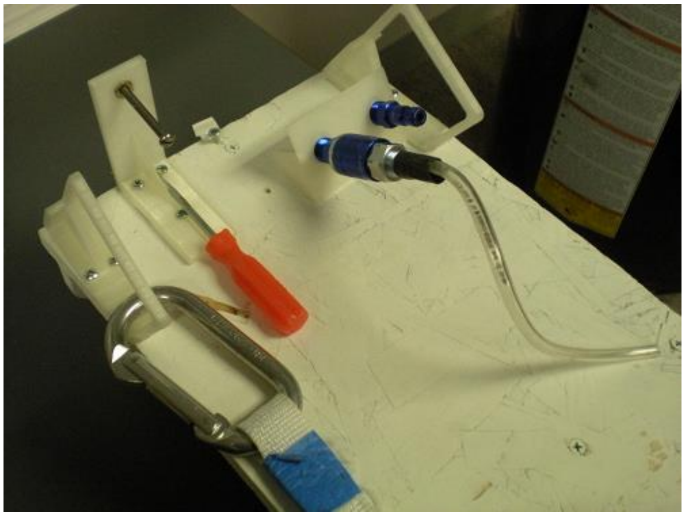

Figure 29. Initial experiment setup displaying a number of tasks required to be performed while wearing the prototype system.

the clip to secure it to the second hand rail was problematic due to the inability to reorient the glove that was noted previously. The lock collar platform presented the least amount of issues however difficulty was experienced when reaching to grasp the collar due to the confined space of the chamber. The difficulties that were encountered during this preliminary test consisted of artifacts that could not be improved by the utilization of the assistive system and thus would not provide any insight into the performance of the design. Thus it was decided that a new experiment had to be devised.

Reflecting back on the characteristics of the final evolution of the design a few points were noted that would help define what "role" a system such as this would fulfill. Due to the bulky fingertip components and relatively slow travel time of the actuators the design was deemed unsuited for rapid and dynamic movement patters. Rather it would provide a greater benefit assisting activities where a sustained grasp was required such as holding onto a handrail or tool. With this in mind a new experiment was developed to test the assistive system's ability to increase the endurance, or postpone the fatigue, of the test subject participating in a sustained grasp. The decided upon object for this grasp test was a baseball. Due to its commonality, most individuals are able to understand the force it takes to grasp it at atmospheric pressure creating a valuable reference point when discussing the data and subject experience gained from the experiment. The details of the new experimental procedure as well as the testing apparatus are presented in the following section.

CHAPTER V

APPARATUS AND PROCEDURE

Apparatus

The apparatus used in the experiment is comprised of a vacuum chamber and vacuum pump. Illustrated in Fig. 30 the chamber itself is a cylindrical pressure vessel that is approximately 26 inches long and 11 inches in diameter. The chamber has two Plexiglas viewing ports, one along the length of the body and one at one of the ends. At the end opposite the viewing port is the interface for the glove assembly. The interface consists of a flat metal ring with a concentric rubber ring and 12 bolt holes spaced evenly around its surface. The glove assembly has an identical metal ring and bolt hole pattern and is secured to the chamber by tightening down each of the bolts evenly, sandwiching the rubber ring, creating an airtight seal. Shown in Fig. 30 the glove assembly consists of the metal ring, as stated previously, and the glove itself. The glove is sewn from leather and has fabric components integrated onto the exterior to create attachment points for the palm bar used to maintain an ergonomic shape when a vacuum is pulled in the chamber. The glove is attached to a rubber lined, ribbed-fabric sleeve via a plastic cuff and secured in place using metal fasteners. The fabric sleeve is what joins the glove to the metal ring and completes the airtight seal inside the chamber. The objects that will be interacted with when a vacuum is pulled must be placed inside the chamber prior to bolting the chamber and glove interfaces together.

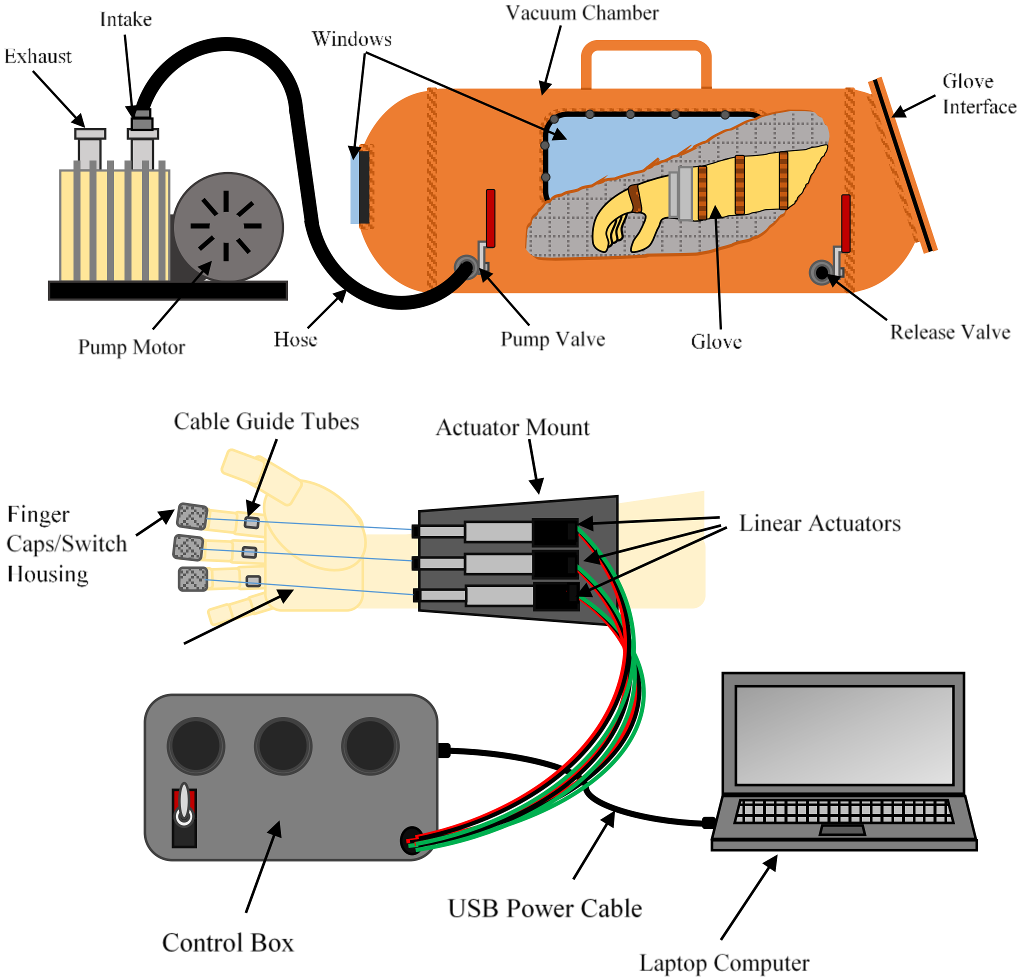

Figure 30. Diagrams of the glove box apparatus and the prototype assistance system with key components labeled.

In addition to the Plexiglas windows the chamber features two valves and a pressure gauge. One of the two valves is hooked up to the vacuum pump to extract the volume of air inside the chamber while the other is used as an emergency release valve to let the air back in. During the experiment the release valve will be used to regulate the internal air pressure as this capability cannot be accomplished with the pump. The vacuum pump has a 0.5 horsepower Franklin Electric motor able to pull a vacuum down of 51.7 mmHg. This is means it is capable of obtaining the required 223 mmHg vacuum to create the 4.3psi pressure differential across the material of the glove. The equipment that is used to record the experiment consists of a video camera and a free standing light to illuminate the interior of the vacuum chamber.

Procedure

Before each test is conducted the apparatus and vacuum pump system were inspected. The bolts holding the glove plate on are checked to ensure a proper seal, the integrity of the hose running between the chamber and the pump is inspected, and the emergency release valve on the chamber is checked for functionality and left in the open position. One minor concern that was noted was a slight kink in the hose running between the vacuum chamber and the pump. This was due to the layout of the system that was chosen to accommodate all of the required equipment on the allocated table space. It did not pose a direct threat to the subject or supervising personnel but was monitored during the experimental process. Once the visual inspection was completed the pump’s oil level needed to be checked once prior to the experiment. This allows the motor within the pump to function nominally and prevents component damage. To do this the pump was switched on and the exhaust port as well as the motor’s auditory signature were monitored for a short period of time to verify proper operation.

Once the chamber and pump system had been verified the recording equipment and peripherals were checked for placement and operation. The light source used to illuminate the interior of the chamber is positioned just outside the window at the end of the chamber and the electrical connection and light bulb are verified. The camera is mounted on a tripod so that the large rectangular window in the side of the chamber, the glove, and experiment are in view. The light source is then switched on and the camera view is checked. At this point the position of the light source can be altered to create a more observable condition in the chamber. Once the conditions have been deemed satisfactory the experiment may proceed.

The activity that will be conducted by the subject during the experiment will be the baseball grip test described previously. The experiment will be conducted in two phases, the first will be without the use of the assistance system and the second will be with it. The footage from each phase will be reviewed and noted for time and additional qualitative parameters from subject feedback after all experiment trials have been completed and will be discussed the in Results and Discussion section. The first phase of the experiment will begin by having the subject insert their hand into the glove adapter and seed their hand within the glove component. If they are having difficulty due to material folding on itself a minor vacuum may be pulled in the chamber to inflate the glove and alleviate this issue. Once the hand is seeded the chamber will be brought back to atmospheric pressure, if a vacuum was pulled, and the camera will be turned on and begin recording the activity within the chamber. The subject will pick up the ball from the chamber base and adjust their grip on the ball until it is in a secure and comfortable position. Once the subject indicates they are ready to proceed the vacuum pump will be turned on and the chamber release valve is closed to begin drawing a vacuum. As the pressure in the chamber decreases the glove will begin to inflate and become relatively stiff, the baseball may slip at this point if the subject was not prepared to cope with this ballooning effect. Should the ball fall at this point the chamber will be vented and they will be permitted to reset the experiment. The EVA suits that U.S. astronauts operate in on the International Space Station are only pressurized to 4.3 psi thus the pressure differential required across the material of the glove is 4.3 psi corresponding to an internal chamber pressure of 10.4 psi. This means that full vacuum is not required and the pressure differential will have to be regulated via the chamber's release valve by the supervising personnel throughout the experiment. Once the operating pressure differential of 4.3 psi is reached the time is noted and the test begins. The subject maintains their grip as long as possible and the test has a maximum run time of 10 minutes. Should the ball be dropped the time will be noted and the chamber valve will be opened, returning the internal atmosphere to 14.7 psi and the subject will be allowed to pick up the ball and resume the test. The subject will be allowed to retry as many times as possible within the 10 minute time frame. However, if the ball is dropped two times in a row within one minute near the end of the testing session it may signify significant muscular fatigue and the test will be terminated to prevent the subject from straining or injuring their hand or arm. Once the test has been completed the subject will drop the ball and remove their hand. Once this is done, the release valve will be opened and the pump will be shut off. At this point the subject is asked to report on the condition of the muscles in the hand and forearm paying attention to any difficulties manipulating fingers and grasping objects or making a fist. This qualitative data is noted and the video footage will be reviewed at a later date. The next test phase will commence when adequate time has passed for the subject's muscles to recover. The time frame for this will be 1-2 hours, depending on the exertion put forth in the previous test, after which the subject will be asked if they are ready to proceed. The subject may request additional time if they do not feel their muscles have recovered.

The second phase of the experiment will duplicate the procedure followed in the first with the addition of the assistive system which requires initial preparatory steps before the subject places their hand inside the glove box. Donning the assistive system requires additional personnel to secure it to the subject’s hand. First the system must be connected to a laptop via the USB cable to power the Arduino board and linear servos. Once the cable is plugged in verify there is power by throwing the toggle switch on the control box to the “ON” position and waiting for the servo motors to move to the preprogramed initial position. If the motors are already in this position they will not move, in which case power should be verified by actuating one of the switches in the fingertip components. If the motors are still unresponsive then there is a break in the circuit and the experiment will have to be postponed until the problem is resolved. If power has been verified then the motors will be set to their fully extended position using the corresponding buttons on the control box. Next the system is donned by the subject by placing their hand through the foam bracer holding the motors keeping the motors facing the user and the lace system facing away from them. Next the subject will place their index, middle, and ring fingers in the corresponding finger cuffs keeping the cable and wiring along the palmar side of the hand. Once the fingers are situated the lace system on the foam bracer is tightened to secure the system to the arm. Next the small tubes that are on the cable that runs between the finger cuffs and the linear actuators are taped to the proximal phalanx of each finger using 0.125 inch Kapton tape. This helps mitigate bowstringing when the motors begin to retract and flex the fingers. Once the system is completely attached to the subject they will actuate the switches in each of the fingers to verify the system is working. Once functionality has been verified a light vacuum will be pulled in the chamber inflating the glove and the subject will place their hand inside the chamber as before. Due to the added bulk of the system some effort is required to situate the hand in the glove. Additionally, the shape and size of the finger cuffs are such that they will not fit all the way into the fingers of the glove. Rather they will rest approximately 0.25 inches from the end of the glove’s fingers. Once the subjects hand is fully seeded in the glove the experimental procedure described above is repeated. The subject will grasp the baseball under partial vacuum for as long as they can in the 10 minute time frame. Upon completion of the experiment the subject will remove their hand from the chamber, the system will be removed, and they will be asked to assess the physical condition of their hand as before. This, along with the time data, will be utilized to determine the degree to which the assistive system effected the performance of the user as well as determine what areas of the design can be improved.

CHAPTER VI

ANALYSIS AND DISCUSSION

The data that is obtained from these experiments is comprised of time values and self-assessments of the test subject’s muscular fatigue. The overall effectiveness of the assistive system’s design will be judged based on both of these factors. The time data is of a quantitative nature thus providing a more direct and concrete way of measuring the effect of the system. Should amount of time the subject is able to grasp the baseball increase by a substantial margin after donning the assistance system then it is reasonable to state the device enhanced the user’s performance in some capacity. The qualitative data obtained from the subject’s self-assessment must be taken into account as well to properly judge the performance of the device. The subject will be asked to report their discomfort level on a 0 – 10 scale, with 0 being no discomfort experienced and 10 being the most discomfort, as well as state any signs of muscular fatigue such as shaking, stiffness, and reduced force output. If the subject reports no marked decrease in muscular stress or the position the system places the fingers in when fully retracted put a new stress on their hand then it has to be noted. Though the system may be able to completely offload the force of the glove it is not a good design if it is not comfortable to use. Additionally the video footage is analyzed thoroughly to note significant events and how they could have affected the outcome of the experiment. One such event would be the ball falling from the subject’s hand. If this occurs once or twice during the experiment then it is not considered significant however, should it occur several times in a row it is reasonable to suspect the time data and self-assessment do not represent the entire situation. When the ball is dropped the clock is stopped and the chamber is vented to allow the subject to reach and pick up the ball once more. The clock will resume when the ball is securely grasped and the required vacuum is pulled in the chamber. This means the muscles are allowed to recover for several seconds thus when the test resumes they will not be in the same physiologic state. Therefore the test results should not be held in the same regard as a subject that dropped the ball once or not at all.

Experiment Results

The data obtained from these experiments painted a rather complex picture of the device's performance and the experiment as a whole, requiring analysis from several different aspects to properly interpret. Before conclusions are fleshed out, an overview and basic interpretation of the raw data is presented to provide the foundation for the analytical process that follows. Contained in Table 2 is the data obtained from each experiment trial, additionally the timelines for each experiment may be viewed in Figs. 31-34 which may be viewed at the end of the chapter. As seen in the table Subject 1 was able to maintain a grip on the baseball for the entire ten minute testing period without the use of the assistance system. Afterward they showed significant muscular fatigue, displaying shaking during both neutral and closed hand positions, an inability to fully flex or extend fingers, and reduced grip strength. Subject 2 and 3 gave comparable performances as shown in the table and figures. Neither was able to make it to the ten minute mark and both dropped the ball during the test. Subject 2 dropped the ball twice while subject 3 only dropped it once. When questioned about these occurrences each reported losing grip of the ball due to the ballooning of the palm when a vacuum was drawn. While this does occur, subject 1 and 4 were able to sustain their grip for the full time period suggesting the influence of additional factors such as fatigue. Interestingly this hypothesis is only supported in the case of subject 2 who voluntarily terminated the experiment reporting significant discomfort and fatigue. While there was no quantifiable method of verifying the subject’s claims, their self-assessment is treated as an adequate substitute. Subject 3's experiment was terminated early by supervising personnel due to concurrent projects. Unfortunately another time could not be lined up to conduct an additional test. However, the post-test evaluation of subject 3 does offer a baseline for their performance with minor tremors and full range of flexion and extension demonstrated. Subject 4 performed comparable to the first subject maintaining a grip on the baseball throughout the duration of the experiment. However subject 4 did not report the same degree of fatigue and was able to demonstrate full flexion, partial extension, and only minor shaking when forming a fist.

With the first set of tests conducted the prototype assistance system was donned by each participant and the procedure repeated. Based on the results of the unassisted test, the greatest improvement in time is expected from subjects 2 and 3. The fatigue that prematurely ended subject 2's test should be mitigated and the solid functionality demonstrated by subject 3 after the initial test bodes well for their endurance capabilities. The first and fourth subjects maxed out the allowed time during the first test therefor the influence of the assistive system will be looked for in their post-test evaluation regarding muscular fatigue. The test with Subject 1 yielded a result akin to what was predicted earlier. The subject dropped the ball three times during the experiment and the overall time was lengthened slightly to accommodate for this and determine if they were able to go beyond their initial performance. As shown in the table, the extended experiment time was not enough to compensate for the amount of time spent retrieving the ball. However, it did bring the total time spent grasping the ball near the ten minute mark. After the experiment Subject 1 reported less strain during the test, and less fatigue demonstrating full flexion and extension of their fingers. Subject 2 showed the greatest quantifiable improvement, extending their performance time by over two minutes or approximately 34% over the unassisted test. Subject 3 and 4 were able to come within 20 seconds of their previous test time however were not able to increase them. The cause is hypothesized to be the number of times the ball was dropped. Both of the subjects dropped the ball 11 times during the testing period and, as displayed in Table 2, the time spent retrieving the ball was over three minutes for Subject 3 and just under three for Subject 4. In spite of this lack of improvement in the quantifiable data, the qualitative assessments of the subjects provided evidence of the device's affect as well as reason for the inability to secure the ball in their hands. Subject 4 noted less fatigue and no shaking after using the system however, they commented on the switch housings greatly reducing their tactility. This made determining if a secure grip had been established difficult leading to the ball slipping from their hands. Subject 3's self-assessment introduced a degree of uncertainty about the system and the experiment. Though their performance was comparable to Subject 4’s, they reported no noticeable reduction in muscular fatigue, increased strain on the hand, and sore fingertips. Upon further investigation the increased strain and sore fingertips were results of the system's design. The decision to only assist the index, middle, and ring fingers placed additional stress on the thumb and pinky and the grip adopted by Subject 3 seemed to exacerbate this. Additionally the hard plastic for the switch houses wore on their fingertips developing the soreness felt after. The reason for the negligible reduction in muscular fatigue however has not been discovered and could be an element unique to this subject's physiology or grip method. These curiosities and additional parameters regarding system performance are looked at further in the following sections.

Fatigue and Recovery

As stated in the procedures, if the ball fell from the test subject's hands the vacuum is released so they may maneuver their hand to retrieve it. Given the current experimental setup, this is the only way to accomplish this task and unfortunately it has a drawback that could influence the results of the tests conducted. Retrieval and recreating the vacuum conditions within the chamber takes time. Using Subject 2's trials as an example it is seen that this period is not large, approximately 16 seconds for three occurrences, however it will compound should the ball continue to be dropped. Subject 3 and 4 each dropped the ball 11 times during their second trial totaling 3 minutes 25 seconds and 2 minutes 40 seconds respectively. This amounts to 34% and 25% of their test time respectively, and thus are not trivial amounts of time. This highlights an ergonomic issue with the system as both were unable to utilize the device to maintain a grip on the baseball. Furthermore the pattern in which these events occur is in consistent, short term intervals so the individual is not working to contain the ball for more than one minute through most of the experiment. This is in stark contrast to the tests with Subjects 1 and 2 where they were working against the ballooning of the glove for several minutes at a time bringing into question what is occurring on a physiologic level during these four test and whether or not they can be compared. To address this a high level investigation was done on the mechanics of fatigue and the nature of the muscle fibers residing in the human body.

Fatigue is the general decline in a muscle to produce force and may be classified as either nervous or metabolic. Nervous fatigue usually occurs when an individual is attempting a movement that their muscles are not trained to do and is often seen among beginning weight lifters[67][68]. Metabolic fatigue occurs when the muscle fibers are running out of fuel to metabolize or when waste products, metabolites, have begun to accumulate in the muscle tissue interfering with the signal sent from the nervous system. Given that using your hands to grip and pick up objects is a common activity that is learned in infancy the type of fatigue experienced in this experiment is most likely metabolic[69].

The intrinsic and extrinsic muscles of the hand, as well as all skeletal muscles in the body, contain two types of muscle fibers which are aptly named slow and fast twitch. Fast twitch fibers are able to contract rapidly using an anaerobic reaction with glycogen as the energy source. They have the highest degree of contraction but fatigue relatively rapidly, depleting their stores within a matter of seconds. The recovery time for these fibers tends to be longer because of their role as rapid, high energy movers[70]. By comparison slow twitch fibers are meant for long duration, low intensity activities. These fibers are smaller in diameter and contain higher concentrations of myoglobin which carry the oxygen required for energy generation. Additionally, they are able to go for longer periods of time

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[67] Gandevia, S., Allen, G., Butler, J., "Supraspinal Factors inhuman Muscle Fatigue: Evidence for Suboptimal Output from the Motor Cortex," Prince of Wales Medical Research Institute, *Journal of Physiology*, 1996, 490.2, pp.529-536.

[68] Gandevia, S., "Spinal and Supraspinal Factors in Human Muscle Fatigue," *Physiological Reviews*, American Physiological Society, vol. 81 no. 4, Jan. 10, 2001, pp.1725-1789.

[69] Hargreaves, M., "Metabolic Factors in Fatigue," *Sports Science Exchange 98*, Department of Physiology, The University of Melbourne, 2005, vol. 18 no. 3.

[70] Fitts, R. H., Widrick, J. J., "Muscle Mechanics, Adaptation with Exercise-Training," *Exercise and Sports Science* Reviews, Department of Biology, Marquette University, Milwaukee, WI, 1996 24:427-473.

without fatiguing and enjoy shorter recovery periods[71]. On average the two fiber types are equally distributed throughout the muscular system however there are areas which contain higher concentrations of one or the other. The hands and eyes tend to contain more fast twitch fibers while postural muscles like the lower back and abdominals contain more slow twitch fibers. Training and genetics do have an effect on these concentrations but for our purposes it is assumed that each subject is on par with the average.

When the subject drops the ball they are allowing their muscles to recover their energy stores and displace metabolites, or waste products that interfere with signals from the nervous system, in preparation for the next time they are recruited. In the case of Subjects 3 and 4 the experiment timeline indicates short durations of exertion followed by rest periods of near equal length. Though it was stated that the hand contains primarily fast twitch muscle fibers, the duration each subject spends grasping the ball exceeds their fatigue period thus the slow twitch fibers must be taking over the workload. Working under this assumption it may be stated that the reason Subjects 3 and 4 experienced less fatigue during the second test was due to the slow twitch muscle fibers' ability to rapidly recover each time the ball was dropped. The same may be said of Subjects 1 and 2 but it is the frequency to which this occurs that makes the difference. The frequent work/rest cycle displayed by the latter two subjects creates more opportunities for recovery to occur, especially since the slow twitch muscles that are hypothesized to be bearing the brunt of the work are able to recover quickly. If this is the case then the data obtained from Subject 3 and 4 is not directly comparable to that from Subjects 1 and 2 reducing the pool of

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[71] Fitts, R. H., Widrick, J. J., "Muscle Mechanics, Adaptation with Exercise-Training," *Exercise and Sports Science* Reviews, 1996 24:427-473.

information that may be used to evaluate the performance of the assistive system. However, this does not mean the data from these tests are useless. A stated earlier their inability to grasp the ball for an extended period of time indicates areas of improvement for the design, a conclusion supported by the statements made in the post-test evaluation. It should be noted that the exact rate of recovery was not determined and will vary based on genetics and conditioning of the muscle in question.

Psychological Factors

One atypical point to consider in this kind of experiment is the mentality of the test subject(s) involved. The reason it appears to be "out of place" is because the experiment does not have any goals related to psychology, it is a test of experimental equipment. However, the mental state and toughness of the individual can affect the data. In particular the subject's mentality toward perceived physical limits and ability to compartmentalize pain or discomfort. A great example of this is Subject 2 who voluntarily terminated their first test due to discomfort and fatigue. Yet, after the test, they displayed no physical signs of fatigue. In comparison, Subject 1 pushed through to the end of the allotted time and displayed relatively significant sign of fatigue including visible tremors. There is a clear variation in mentality which caused Subject 1 to compartmentalize any discomfort and continue while Subject 2 opted out of pushing their muscles any further. This highlights an interesting issue for comparing data sets of individuals or at the very least introduces another factor that must be considered. A participant that is very headstrong may make a poor subject because they would be less likely to report discomfort or pain and notice little to no difference after donning an assistive system like the one created for this study. That is not to say that their body does not experience a difference physiologically but psychologically they have trained themselves to deal with pain. So rather than paying attention to what their muscles are “telling” them they compartmentalize the pain, focus on the task at hand, and push themselves as long as possible. Thus when they report on their condition after the test they may not realize how fatigued they really are unless subjected to a grip strength test or a similar metric. Due to the fact that this personality type is more likely to reach the end of the designated test period, any benefit provided by an assistive system is determined through a qualitative self-assessment which is where their psyche downplaying the pain could skew the data. Based on this it would indicate that the ideal test subject should be acutely aware of their condition and be able to note discomfort, fatigue, and any additional parameters to provide a baseline that will determine the effect of a system such as the one tested in this experiment. Furthermore, though it was not conducted during this experiment, a quantitative measure of fatigue is recommended for future experiments to remove this bias.

Limitations of System Design and Selected Hardware

From the start of the project the idea of integrating the prototype system into the glove was played around with and ultimately discarded when it proved an improbable task with the current timeline and resources available. Thus the intent became to add the system onto an existing spacesuit glove to create an ad-hoc experimental system. As discussed previously, this method was met with a degree of success however there were problems noted with ergonomics and actuation characteristics that were, in theory, brought about by electing not to merge the system components with the glove. By securing the cables and fingertip caps directly to the subject's hand rather than the interior of the glove what occurred during the tests was an inefficient transfer and improper transmission of force. As the motor retracts in response to the activation of a switch it pulls on the cable which in turn pulls on the finger causing it to flex. Outside of the glove this mimics the natural motion of the anatomy with a fair degree of accuracy. However, when the system was operated within the confines of the glove the fingers of the garment would not completely replicate this motion causing the ends of the digits to curl slightly within these spaces. If the system had been integrated into the garment the force from the actuators would have been delivered directly to the skin of the bladder, creating the deformation that was sought after in the original concept. Though the devices' performance suffered another characteristic of this type of system was revealed regarding techniques for efficient force transfer. A second limiting factor that was discovered during the development of the project was the Arduino microcontroller board.

As stated in the project development section, the Arduino microprocessor used for this project is a very robust hobbyist board. It is capable of calculations and process far more complex that what this project demands. While this may seem like a benefit, its robust nature can actually hinder the maturity of the design as volume is occupied by superfluous hardware. This tends to be a symptom of commercial off-the-shelf components because the manufacturers must create a product that is marketable. With hobbyist boards this is typically done by broadening the scope of possible applications. This is a valuable characteristic during the initial phases of design where hardware and software requirements are still being determined and the peripheral components are in flux. However, as a prototype matures it behooves the designer to shift away from a general purpose project board and create custom circuity with only the required components. This leads to the creation of a smaller, lighter, and possibly lower power system. Furthermore, commercial boards like the Arduino can impose limitations on a system's design. For example the number of onboard input/output channels contributed to the choice of limiting the number of digits that would be powered to three. The number of voltage, PWM, and digital input pins could not support more than this number. There exists additional hardware to expand the capabilities of the Arduino platform however it doubles the size of the system and, depending on what the peripheral board is, could require additional power sources. Another limitation of the microprocessor is the architecture of the processor itself. The Atmega328 chip on the board has a clock speed of 20 Hz and works on an 8-bit advanced RISC, reduced instruction set computing, architecture[72]. Though it is able to handle the data bandwidth of the current prototype, the previous iteration required additional data processing and the lag between sensor activation and the board signaling the motor to move was noticeable. As stated previously, this was one of the reasons a simpler design was chosen however if capabilities are added to the system it could increase the data overhead and incur the same problem. Mitigation may be found in, again, creating custom circuit boards and selecting hardware that meets the design's requirements.

Another aspect of the design limiting the system's performance was the actuator selected. The Firgelli linear actuators that were selected represented the "middle of the road" option of the actuators available for purchase. As stated in the Development section they had a stroke length of 50 mm, gearing ratio of 100:1, and a static hold force of 80 N. The speed at which the lead screw was extended or retracted ranged from 6 – 12 mm/s

---

[72] "8-bit AVR Microcontroller with 4/8/16/32K Bytes In-System Programmable Flash," ATMEL Corporation, 2009, http://www.atmel.com/Images/doc8161.pdf, pg 1.

depending on if speed or power were favored during operation. The component offered a compromise between power and speed because it was unknown at the time what force level would be required and what speed would be the most ergonomic. It was guessed that faster would be better given the quick twitch nature of our phalanges but the force output was not as great due to the nature of the gearing. The required stroke length of the motor was another unknown and again, it was decided to purchase the motor that was between the shortest and the longest offered. If it turned out to be too long, the maximum length could be adjusted using software. If it turned out to be too short then either a different unit would be purchased if time allowed or the hindrance would be noted and testing would be carried out regardless. During the experiment it was found that the stroke length could have been longer and the speed could have been quicker at the cost of force output. The motors did not have an issue holding up against the pressure of the glove indicating that an experiment should have been done to determine the minimum force needed to deform the garment. Furthermore the chosen linear actuator is akin to a servo motor as far as complexity and control strategy. They have the same input wires and position is controlled using pulse width modulation. As a result they are able to be easily integrated into the current control architecture but should a more complex architecture be desired another motor must be adopted.

A final design characteristic that is postulated to limit the potential of the system was the decision to omit assisting the thumb. Specifically noted by Subject 3, by developing a system that only powered the index, middle, and ring fingers it required the adoption of atypical grip patterns. These grip patterns create unnatural recruitment patterns that strain the muscles involved and may cause the experiment to be terminated prematurely. However, the amount of time required to develop the architecture of a thumb component was deemed too great for the additional functionality gained. Furthermore, properly securing the cables required to mimic the thumb's motion, particularly opposition, would have required the integration of the system into the garment. This does not mean the inclusion of the thumb is superfluous. On the contrary, the thumb is a key factor in successfully grasping an object and should be included in the initial design of subsequent assistance systems.

3D Printing

The growing popularity of 3D printing has brought an entirely new level of capability to the average consumer. Individuals now possess the capability to design and manufacture tools, spare parts, intricate knick-knacks, and even firearm components. The versatility of these machines is limited only by the imagination of the user, couple this with the rapid turnaround time they are able to provide and what results is a manufacturing capability ideally suited for prototype development. The specific machine used during the project was the Makerbot Replicator 2 which extrudes the selected building material though a nozzle mounted on a small gantry system with two degrees of freedom. The third degree of freedom comes from the build platform which is attached to a lead screw that moves it up and down. The machine is able to create 3-dimensional structures by layering "slices" on top of one another, essentially constructing an item from the ground up. Though the sole material used in this project was ABS plastic, the raw materials available to filament fed printers include flexible rubbers, carbon fiber matrices, and even metal composites.

The versatility of this technology is truly astonishing however, it was found during the project's development that some of the components being designed presented issues in manufacturing. Even with the 100 micron printing resolution[73] the software algorithms used to "slice" computer models into machine code, support overhanging structures, and fill in solid segments often interfered with the intentions of the designer. As stated in the section on project development, a test run of several components was conducted to determine the limits of this manufacturing process and the resultant data helped improve the design of existing components and progressed the system as a whole. It is advised that additional effort and time be placed in getting to know the limits of this technology even further, including factors such as the temperature of the extruder tip and the effect of ambient room conditions. Though it will take time, becoming a technical expert of this capability will provide great benefit to the designer(s) that utilize it for future projects.

Future Development and Research Directions

The prototype developed and tested during this project represented the first approach at a unique concept. As shown in the Literature Review there are a handful of prototype assistance systems developed specifically for spacesuit gloves, yet this particular approach is unique among them. Thus this system was kept simple to demonstrate a measure of mechanical functionality rather than focus on testing an advanced concept. As the design evolved a greater understanding of this category of system was achieved and along with it areas of improvement were identified. Though these were not implemented during this project, they are listed as recommendations should development of this system continue.

---

[73] "Makerbot Replicator 2 Desktop 3D Printer User Manual," *Specifications,* http://downloads.makerbot.com/replicator2/MakerBot_Replicator2_user_manual.pdf pg 6.

First and foremost, the next generation of this concept should include all five fingers rather than a subset as was done previously. During normal grip patterns all of the fingers play a role and by excluding the thumb and pinky from the system it caused the test subjects to adopt atypical grasp techniques during each experiment. Though it is reasonable to assert that the subjects would adapt their techniques given enough practice, ideally the system should not impose such conditions on the operator. The second recommendation is the integration of the system into the garment. As discussed previously attempts were made to integrate the cable and switch components into the bladder. However, to fully take advantage of the utility these systems can offer they must be merged with the glove at a fundamental level. This creates a high degree of complexity as the garment itself would be redesigned around this system to produce an entirely new garment component. The added complexity does create a larger chance of failure and the risk may be deemed too great, however to ensure efficient force transfer to the garment as well as an increased ergonomic experience it is advised steps be taken to facilitate this proposal. Aside from these two statements, there were several smaller recommendations formulated regarding the approaches chosen for each of the subsystems.

The cables that were used to transfer the force of the motors to the fingers served their purpose however, they were relatively large in diameter and their presence was noticeable during the experiments. To mitigate this smaller diameter cables are recommended as long as the tensile strength is sufficient. Decreasing diameter can increase the risk of the cable breaking thus selecting a polymer, such as that used in heavy weight fishing line, is preferred. Custom etched circuit boards rather than off the shelf hobby boards should be adopted as the design matures. As mentioned previously the versatility of the Arduino was a great asset during the initial phases of design when components were being changed frequently. But as the design begins to close in on its final rendition the computing requirements become better defined negating the need for a versatile platform. Custom electronics units can also reduce the size and power requirements of the system making it more conducive to evolving into a self-contained unit rather than being tethered to a control box and laptop computer.

A new method, or new sensor array, for triggering the actuators would also benefit the evolution of the system. The momentary switches worked well, however they are large and the finger caps designed to contain them ended up being too bulky preventing the hand from being properly seeded in the glove. A solution to this is to use conductive fabrics to create electrodes at specific points in between the layer of the garment with thin layers of insulating material separating them. As the operator deforms the glove it will compress the insulating material to the point of causing its properties to break down and allowing a current to flow through it thus mimicking the function of the momentary switches. Another suggestion for this subsystem is to continue development with flex sensor technology to determine how to improve its implementation. The CyberGlove company is able to market products using this concept to interpret movement with a high degree of accuracy. Furthermore, increasing the processing speed could potentially solve the lag experienced due to signal process and experimentation should be done to determine if the subsequent effects on system power and size outweigh the benefits of this technology. A tangential point to this would be the addition of a sensor or mechanism that would provide a feedback signal to the control software indicating to the system and the user that they have successfully grasped an object. This may be accomplished by placing a pressure sensor on the pulp of the fingers and creating software that would halt motor actuation upon the sensor's signal passing a specified threshold. This stop condition may be supplemented by adding vibrotactile displays or minute vibrating components to the interior of the garment would provide a tactile sensation when interacting with an object. Both of these additions would aid in facilitating a better user experience as they would be receiving a form of input from the environment they are interacting with.

The final recommendation is in regards to the testing procedures. As stated earlier, the effects of a subject's psychological profile on the experiment are unknown and it could have the greatest impact on the validity of collecting qualitative data from experiments like this. The concern lies primarily with querying subjects about their physical condition as some degree of bias will persist even if the candidates pass a screening process. However since the objectives of this experiment were not concerned collecting data on the subjects themselves then, as stated earlier, it is recommended that only quantitative methods of data gathering be utilized. Suggested parameters include measuring force output before and after each test and determining the range of motion of each digit in flexion and extension with and without the system.

Table 2. Time data obtained from each subject with corresponding breakdowns for time spent grasping the baseball and time spent out of vacuum.

	Subject 1		Subject 2		Subject 3		Subject 4	
	Unassisted	Assisted	Unassisted	Assisted	Unassisted	Assisted	Unassisted	Assisted
Experiment Length (MM:SS)	10:27	11:18	07:41	09:15	08:04	11:07	09:52	10:44
Number of Drops	0	3	2	2	1	11	0	11
Grip Time (MM:SS)	10:25	09:40	07:26	09:02	07:53	07:42	09:52	08:10
Time Out of Vacuum (MM:SS)	00:00	01:37	00:15	00:13	00:11	03:25	00:00	02:34

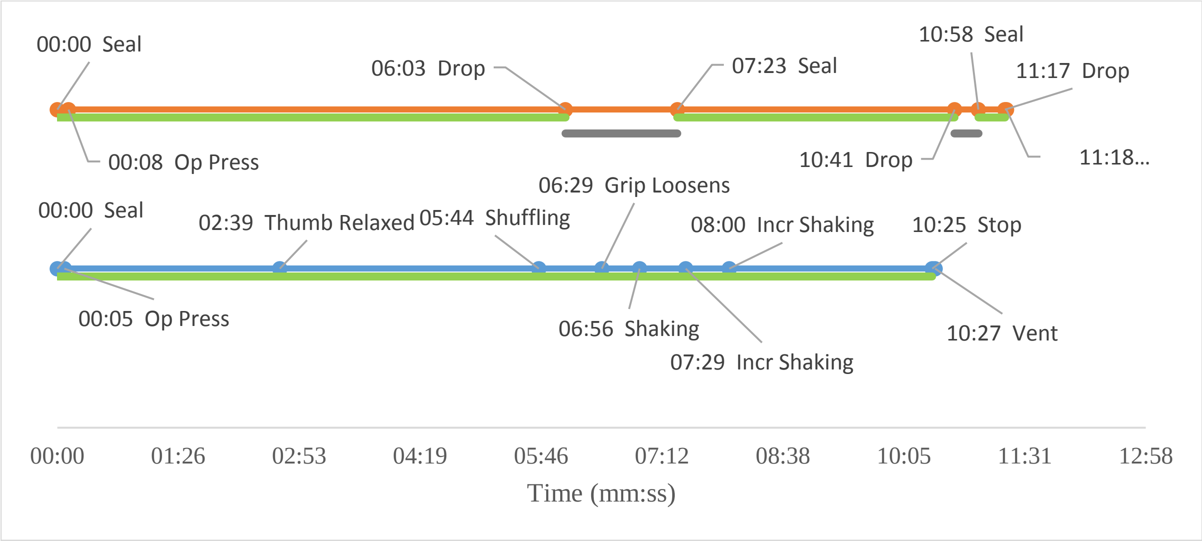

Figure 31. Experiment timelines for Subject 1 without the assistive system (blue) and with the assistive system (orange), with the time spent grasping baseball (green) and time spent resetting experiment after ball was dropped (grey) marked.

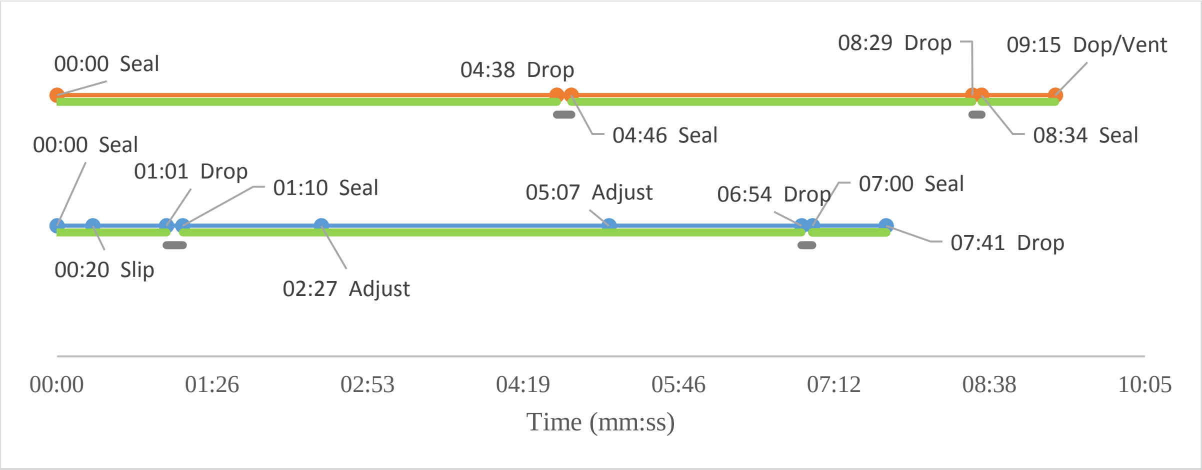

Figure 32. Experiment timelines for Subject 2 without the assistive system (blue) and with the assistive system (orange), with the time spent grasping baseball (green) and time spent resetting experiment after ball was dropped (grey) marked.

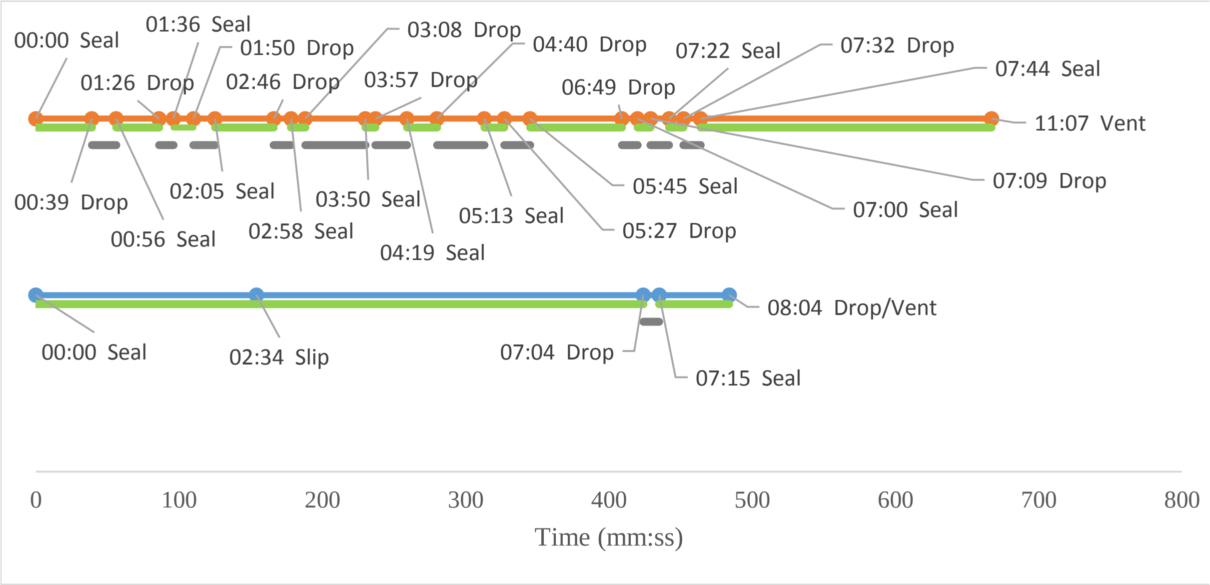

Figure 33. Experiment timelines for Subject 3 without the assistive system (blue) and with the assistive system (orange), with the time spent grasping baseball (green) and time spent resetting experiment after ball was dropped (grey) marked.

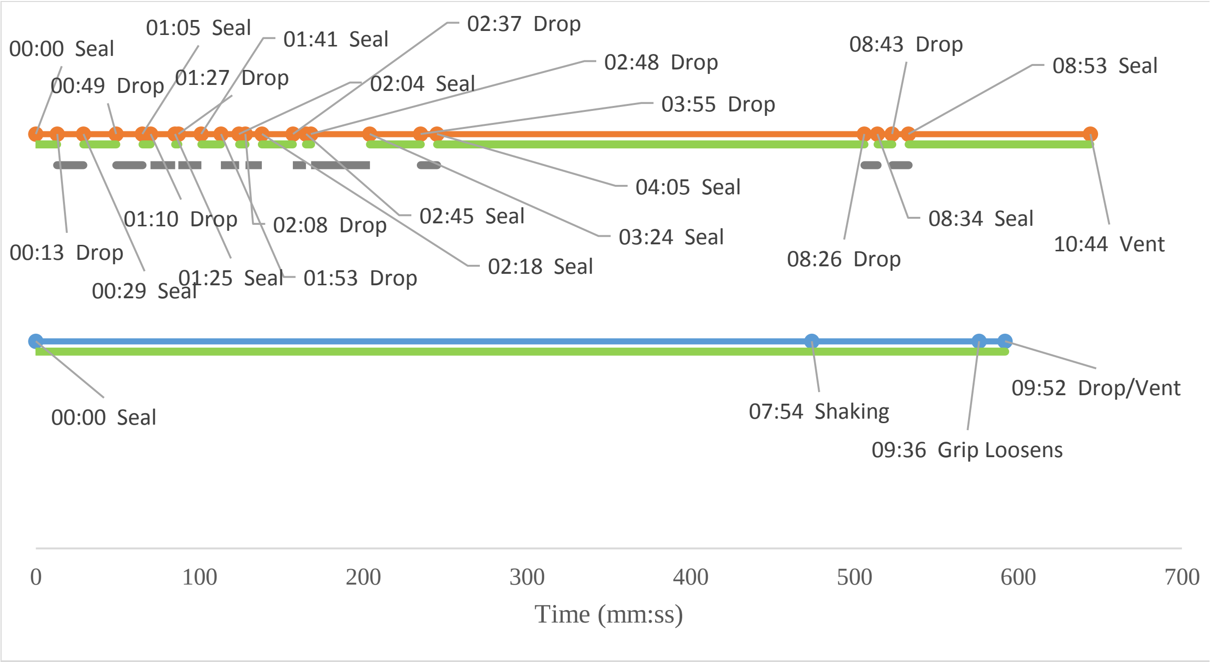

Figure 34. Experiment timelines for Subject 4 without the assistive system (blue) and with the assistive system (orange), with the time spent grasping baseball (green) and time spent resetting experiment after ball was dropped (grey) marked.

CHAPTER VII

CONCLUSIONS

The design and manufacture of EVA gloves has greatly improved over the decades, integrating new technologies and pattern concepts that greatly improve the garment's fit. However, when the spacesuit is pressurized it balloons outward and the elasticity of the bladder creates resistance to deformation. Astronauts operating in EVA suits have to constantly work against this force to perform tasks which cause the muscles to fatigue, especially after six to eight hours of activity. One area this is particularly significant is in the glove due to the high degree of mobility the garment must try and facilitate. In an attempt to mitigate this resistance an electro-mechanical assistance system was developed and tested utilizing techniques and technologies noted from previous prototypes. The development of the system is detailed in the document and overall it the undertaking was a success with each of the project objectives being met. The effect of the assistance system is best displayed in the qualitative data obtained after each test with three of the four subjects reporting noticeable reduction in muscular fatigue. The quantitative time data unfortunately is not able to support this conclusion because inconsistences prevent an overarching trend from being observed. There was one subject that displayed a significant increase in activity time when utilizing the assistance system, however the other three experienced difficulties when operating the system which caused significant portions of the allotted experiment time to be lost.

There were several areas of improvement and system specific insights discovered during the development process and a solution has been proposed for each should development continue on this system. 3D printing served as an excellent manufacturing process for prototyping with fast turnaround times allowing large numbers of component concepts to be tested. The Arduino microcontroller, as well as other hobby electronics boards, function well in the early phases of design but as hardware and processing requirements become better defined custom electronics components are better suited for the task. The actuators and force delivery method selected performed well for this rough prototype however further refinement is recommended including reducing the size of the cables and related components and tuning the actuators to further increase the system's ergonomics. One unforeseen factor which potentially affected the data obtained from the experiments was the psychological state of the test subjects. As discussed previously the qualitative data obtained through self-assessments could be subject to a degree of bias, though the effects of this were not investigated. Ultimately it was recommended that data obtained from experiments such as these remain quantitative in nature to mitigate this occurrence.

The knowledge gained from this project has been immense and brought to light the potential that lies in creating exoskeleton-like components for space applications. As mentioned in the beginning of the document, the alternatives that have been proposed to the current spacesuit architecture have met with significant difficulties in terms of material properties and cost to benefit ratios. This is where efforts into integrating these kinds of systems into spacesuit technology may find their niche. It is recognized that these efforts would greatly increase the complexity of EVA suit systems and when the health and well-being of a human is brought into the picture, risk reduction is a primary design driver. However, the potential utility gained is staggering because one could create a suit that employs mechanical components in multiple areas or even additional technologies that give the individual increased situational awareness as well as access to biometric and mission critical data. Though these capabilities may be unnecessary for current low-Earth orbit operations, increasing the ability of the crew to function autonomously is crucial for deep space operations. Though human missions to other planets and remote locations in the solar system are generally relegated to the realm of science fiction, efforts are being carried out to change this and it is recommended that exoskeleton robotics become part of these efforts.

APPENDICES

Arduino Code

Script Experimenting with Pressure Sensor Triggering Stop Condition

```
/* 7/7/14 code sketch test the idea of using a pressure sensor
to halt the movement of the linear actuator to create a more
robust system that can respon properly without the need
for complex internal modeling and extended code runtime.*/

#include <Servo.h>;
Servo linear;
const int flex = A0;
const int pres = A1;

int flexVal = 0, presVal = 0;

//create and initialize variables to calibrate the system
int flexMin = 1023;
int flexMax = 0;

//System Setup Loop
//Objectives: Begin Serial Comms
//            Attach Actuator(s) to PWM Pins
//            Calibrate the System

void setup(){
  Serial.begin(9600);
  linear.attach(9);
  while(millis()<5000){
    flexVal = analogRead(A0);
    if(flexVal > flexMax){
      flexMax = flexVal;
    }
    if(flexVal < flexMin){
      flexMin = flexVal;
    }
  }
}

//System Op Loop, includes if statement for pressure sensor

void loop(){
  flexVal = analogRead(A0);
  presVal = analogRead(A1);
  int pos = map(flexVal, flexMin, flexMax, 0, 100);

  if (presVal <= 860){
    linear.write(pos);
  }
  Serial.println(presVal);
```

```
  delay(1);
}
```

Script for Variable Resistor Architecture

```
/*
Script for EVA Exoskeleton. This code serves to first calibrate
the sensor inputs to the maximum and minimum positions of their
respective actuators. Once this is done the analog inputs
are read into the board and mapped then constrained to the limits
of the actuator's limits. The actuators are then activated in
proportion to the mapped value.
*/

#include <Servo.h>;

//create objects for the actuators
Servo linear1;
Servo linear2;

//pin assignments
const int psens1 = A0;
const int psens2 = A1;
const int LED = 2;

//create and inititalize variables for sensors and calibration
int sensVal = 0;
int sensVal2 = 0;
int sensMin = 1023;
int sensMax = 0;
int sensMin2 = 1023;
int sensMax2 = 0;

//setup loop begins serial comms and attaches motors to their
//PWM pins
void setup(){
  //begin Serial comms at 9600 bps
  Serial.begin(9600);
  //attach the actuators to their PWM pins
  linear1.attach(9);
  linear2.attach(10);

  //*****CALIBRATION LOOP*******
  //turn on LED to indicate calibration has started
  pinMode(LED, OUTPUT);
  digitalWrite(LED, HIGH);

  //start calibration for 5 seconds
  while(millis()<5000){
```

```
    sensVal = analogRead(A0);
    sensVal2 = analogRead(A1);
    //obtaining new max/min values
    if(sensVal > sensMax){
      sensMax = sensVal;
    }
    if(sensVal < sensMin){
      sensMin = sensVal;
    }
    if(sensVal2 > sensMax2){
      sensMax2 = sensVal2;
    }
    if(sensVal2 < sensMin2){
      sensMin2 = sensVal2;
    }
  }

  //turn off LED
  digitalWrite(LED, LOW);
}

//primary loop reads sensor inputs, maps them to actuator
//limits, and writes the values to the PWM pins
void loop(){
  //read sequence and output for actuators, copy and paste
  //for each actuator added

  //*****ACTUATOR 1*******
  //read the sensor inputs
  sensVal = analogRead(A0);
  //map the sensor values to the actuator's limits
  int pos = map(sensVal, sensMin, sensMax, 0, 179);
  //constrain the values to elimintate outliers
  pos = constrain(pos, 0, 179);
  //initiate the old pos value for threshold calc
  int posold;

  //*****ACTUATOR 2*******
  //read the sensor inputs
  sensVal2 = analogRead(A1);
  //map the sensor values to the actuator's limits
  int pos2 = map(sensVal2, sensMin2, sensMax2, 0, 179);
  //constrain the values to elimintate outliers
  pos2 = constrain(pos2, 0, 179);
  //initiate the old pos value for threshold calc
  int posold2;

  //----------ACTUATION OF MOTORS---------------------

  //Noise was noticed at the low end of the analog readings,
  //value bounced between 0 and 1 frequently without user input
  //creating motor jitter. The "if" statement creates a threshold
```

```
  //to solve this issue.
  if(pos >= 2 && abs(pos - posold) > 5){
    linear1.write(pos);
  }
  if(pos2 >= 2 && abs(pos2 - posold2) > 5){
    linear2.write(pos2);
  }
  //store old pos value(s) for threshold calcs
  posold = pos;
  posold2 = pos2;
  //delay for stability
  delay(1);
}
```

Script for Momentary Switch Architecture

```
/*
Script to operate standard servo motors with two buttons per
motor to control direction.
*/

#include <Servo.h>

Servo motor1;
Servo motor2;
Servo motor3;
const int indexR = 18;
const int indexE = 2;
const int middleR = 4;
const int middleE = 7;
const int ringR = 16;
const int ringE = 14;


int pos1 = 1500;
int pos2 = 1500;
int pos3 = 1500;
int IRbuttonState = 0;
int IEbuttonState = 0;
int MRbuttonState = 0;
int MEbuttonState = 0;
int RRbuttonState = 0;
int REbuttonState = 0;

void setup()
{
  pinMode(indexR, INPUT);
  pinMode(indexE, INPUT);
  pinMode(middleR, INPUT);
  pinMode(middleE, INPUT);
```

```
  pinMode(ringR, INPUT);
  pinMode(ringE, INPUT);
  motor1.attach(10);
  motor2.attach(11);
  motor3.attach(9);
  Serial.begin(9600);
}

void loop()
{

  IRbuttonState = digitalRead(indexR);
  IEbuttonState = digitalRead(indexE);
  MRbuttonState = digitalRead(middleR);
  MEbuttonState = digitalRead(middleE);
  RRbuttonState = digitalRead(ringR);
  REbuttonState = digitalRead(ringE);

  if(IEbuttonState == HIGH && pos1 < 2000){
    pos1 = 5 + pos1;
    motor1.write(pos1);
    Serial.println(pos1);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(IRbuttonState == HIGH && pos1 > 1050){
    pos1 = pos1 - 5;
    motor1.write(pos1);
    Serial.println(pos1);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(MEbuttonState == HIGH && pos2 < 2000){
    pos2 = 5 + pos2;
    motor2.write(pos2);
    Serial.println(pos2);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(MRbuttonState == HIGH && pos2 > 1050){
    pos2 = pos2 - 5;
    motor2.write(pos2);
    Serial.println(pos2);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
```

```
    delay(1);
  }
  if(REbuttonState == HIGH && pos3 < 2000){
    pos3 = 5 + pos3;
    motor3.write(pos3);
    Serial.println(pos3);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(RRbuttonState == HIGH && pos3 > 1050){
    pos3 = pos3 - 5;
    motor3.write(pos3);
    Serial.println(pos3);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
delay(5);
}
```

Script Experimenting with Feedback for Momentary Switch Architecture

```
/*
Script to operate the linear actuator with two buttons.
One of the buttons extends the actuator and the other
retracts it.
*/

#include <Servo.h>

Servo linear;
const int ePin = 2;
const int rPin = 18;
//const int ledPin = 13;

//int pSense = analogRead(A0);
int pos = 1500;
int EbuttonState = 0;
int RbuttonState = 0;

void setup()
{
  //pinMode(ledPin, OUTPUT);
  pinMode(ePin, INPUT);
  pinMode(rPin, INPUT);
  linear.attach(9);
  Serial.begin(9600);
}
```

```
void loop()
{
//determine if the pressure sensor if statement should encompass
//the other two if statements or be incorporated into them, it
//is unknown which will create better functionality, need to test
//both in the system before decision is made.
  EbuttonState = digitalRead(ePin);
  RbuttonState = digitalRead(rPin);
 // pSense = analogRead(A0);
 //if(pSense < 960){
  if(EbuttonState == HIGH && pos < 2000){
    pos = 5 + pos;
    linear.write(pos);
    Serial.print(pos);
    Serial.print("\t");
   // Serial.print(pSense);
    Serial.println();
   // digitalWrite(ledPin, HIGH);
    delay(1);
  }
  if(RbuttonState == HIGH && pos > 1050){
    pos = pos - 5;
    linear.write(pos);
    Serial.print(pos);
    Serial.print("\t");
    //Serial.print(pSense);
    Serial.println();
    //digitalWrite(ledPin, HIGH);
    delay(1);
  }

//use to determine the value of the sensor during a solid grip
//Serial.println(pSense);
delay(10);
}
```

Script Controlling Linear Servo Motors with Momentary Switch Architecture

```
/*
Script to operate linear servo motors with two buttons per
motor to control direction.
*/

#include <Servo.h>

Servo motor1;
Servo motor2;
Servo motor3;
const int indexR = 18;
const int indexE = 2;
const int middleR = 4;
const int middleE = 7;
```

```
const int ringR = 16;
const int ringE = 14;

//int pSense = analogRead(A0);
int pos1 = 1500;
int pos2 = 1500;
int pos3 = 1500;
int IRbuttonState = 0;
int IEbuttonState = 0;
int MRbuttonState = 0;
int MEbuttonState = 0;
int RRbuttonState = 0;
int REbuttonState = 0;

void setup()
{
  pinMode(indexR, INPUT);
  pinMode(indexE, INPUT);
  pinMode(middleR, INPUT);
  pinMode(middleE, INPUT);
  pinMode(ringR, INPUT);
  pinMode(ringE, INPUT);
  motor1.attach(10);
  motor2.attach(11);
  motor3.attach(9);
  Serial.begin(9600);
}

void loop()
{
//determine if the pressure sensor if statement should encompass
//the other two if statements or be incorporated into them, it
//is unknown which will create better functionality, need to test
//both in the system before decision is made.
  IRbuttonState = digitalRead(indexR);
  IEbuttonState = digitalRead(indexE);
  MRbuttonState = digitalRead(middleR);
  MEbuttonState = digitalRead(middleE);
  RRbuttonState = digitalRead(ringR);
  REbuttonState = digitalRead(ringE);
  //pSense = analogRead(A0);
 //if(pSense < 960){
  if(IEbuttonState == HIGH && pos1 < 2000){
    pos1 = 5 + pos1;
    motor1.write(pos1);
    Serial.println(pos1);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(IRbuttonState == HIGH && pos1 > 1050){
```

```
    pos1 = pos1 - 5;
    motor1.write(pos1);
    Serial.println(pos1);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(MEbuttonState == HIGH && pos2 < 2000){
    pos2 = 5 + pos2;
    motor2.write(pos2);
    Serial.println(pos2);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(MRbuttonState == HIGH && pos2 > 1050){
    pos2 = pos2 - 5;
    motor2.write(pos2);
    Serial.println(pos2);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(REbuttonState == HIGH && pos3 < 2000){
    pos3 = 5 + pos3;
    motor3.write(pos3);
    Serial.println(pos3);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
  if(RRbuttonState == HIGH && pos3 > 1050){
    pos3 = pos3 - 5;
    motor3.write(pos3);
    Serial.println(pos3);
    //Serial.print("\t");
    //Serial.print(pSense);
    //Serial.println();
    delay(1);
  }
//use to determine the value of the sensor during a solid grip
//Serial.println(pSense);
delay(5);
}
```

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