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Optimization of Prosthetic Hands: Utilizing Modularity to Improve Grip Force, Grasp, and Versatility

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OPTIMIZATION OF PROSTHETIC HANDS: UTILIZING MODULARITY TO IMPROVE
GRIP FORCE, GRASP, AND VERSATILITY

By

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Bachelors of Science – Biology: Neuroscience

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A thesis submitted in partial fulfillment
of requirements for the

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ABSTRACT

OPTIMIZATION OF PROSTHETIC HANDS: UTILIZING MODULARITY TO IMPROVE GRIP FORCE, GRASP, AND VERSATILITY

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It has been demonstrated that although many varieties of upper limb prosthetics exist, commercially available prosthetics are outdated and unsatisfactory. Ineffectiveness and limitations have led to some prosthesis wearers having to own multiple devices, whereas others have given up on them entirely. Even though ample research has been conducted to design and test new hand designs, the industry appears to rest in an overall stagnated state.

It was proposed here, that one problem with prosthetic research is an excess of variables involved in testing, and therefore the improper application of the scientific method. It seems that

each time a research team desires to test a new idea, a completely new hand and system is designed to house it. A costly and time-consuming cycle is then initiated which may lead to comparing the merits of one hand to the performance of distinct hand designs with multiple differences. Since these comparisons involve multiple variables, the results are often inconclusive and many projects end up shelved.

To help advance prosthetic improvement, it seems necessary to unclog the process by lowering costs, speeding up development, and implementing an improved basis for comparison. The proposed method for achieving the first two objectives is to make use of a 3D printed hand platform. Such prosthetics are durable, inexpensive, and quick to manufacture and assemble. This allows for rapid transition from idea to prototype, and from observation to improvement. The method for improving comparison is the addition of modularity into the prosthetic. If a single hand could be reconfigured to implement different attributes and ideas, the merit of each innovation could be independently demonstrated and verified.

In this research, a 3D printed hand was chosen which could accommodate configurations capable of adding adaptation as well as a resting state of partial curvature to the basic hand. The various configurations, including neither, each, and both changes were then tested in a series of experiments. These were arranged to discover the maximum weight that could be sustained while the hand attempted to maintain grasp on various bar shapes. These tests were run in two different test setups: attached to a non-amputee's arm and suspended by clamps, in order to determine the influence introduced by the limitations of human strength and physiology. These rounds of testing successfully demonstrated that small modifications to the prosthetic could yield improvements in performance (even with a basic, low-cost hand), and that the merit of various ideas can be independently demonstrated on a singular platform.

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1. INTRODUCTION

1.1 BACKGROUND

The basic intent of any prosthetic is to provide form or function to individuals who may be missing part of their body. This meaning was succinctly captured when the term prosthesis was coined, as it stemmed from the Latin words *pros* meaning “to” and *tithenai* meaning “put or place”; the combination indicating something which one would “add to” the body [1]. The idea to substitute something man-made for an absent body part has existed for thousands of years, as historical and physical evidence of replaced limbs or digits has been found for both the ancient Roman and Egyptian civilizations [2-3].

Although the intent is quite simple, the complication in the subject emerges when one factors in the affected area of the body, the impact that absence has on the life of the individual, as well as the vast variety of replacement strategies that could be pursued. When something is missing from the body, the initial impact is commonly three-fold for that area; difference of appearance, loss of sensation, and loss of motion [4-6]. These ramifications further expand when one considers that these factors may affect the capability and autonomy of the individual, and may have personal, social and professional ramifications [5]. When individuals are fitted with a prosthetic, one is chosen based around their wants, needs, and financial means – often after some measure of compromise has taken place.

1.2 UPPER LIMB ABSENCE

Although any physical impediment comes with unique challenges and consequences, the lack of all or part of the upper limb can be particularly impactful. The human hand is a crucial

means of interaction with the world, and as such, it can be said that countless objects have been designed around manual interaction. Through its involvement in daily tasks, the hand is used in ways such as obtaining tactile information, initiating physical labor and object manipulation, and facilitating communication. These varied and essential functions are what makes upper limb prosthetic development challenging, as it is difficult to replace such a complicated and important tool.

The degree of upper limb absence can be divided up into different categories, and the most significant separator between them is which joints and muscles are available for the individual's use, and which will need to be replaced.

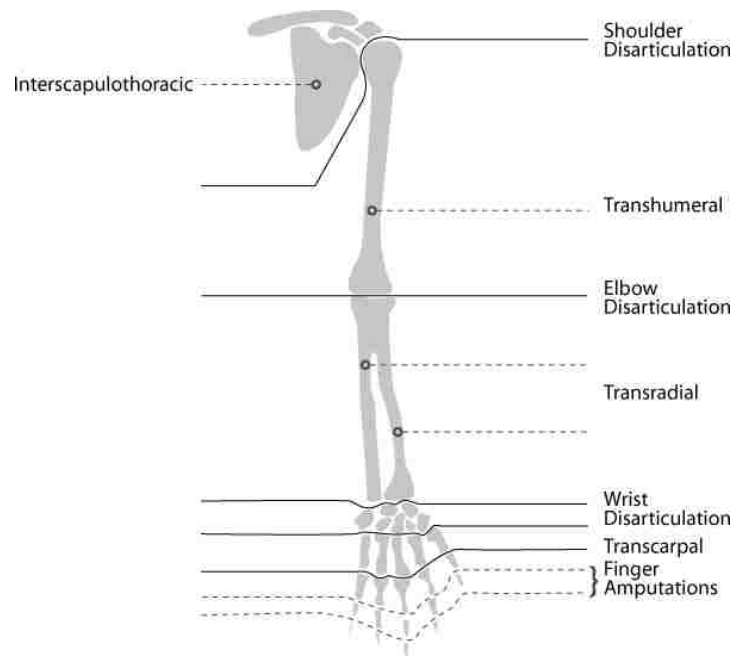


Figure 1.1: Upper Limb Amputation Classifications [7]

A significant number of people are living without some portion of their upper limb, and the most prevalent subset involves the absence of one or more digits. Worldwide estimate place some form of upper-limb reduction at 1 out of 100 to 2000 live births, and that population only increases when eventual accident or amputation are factored in [8]. In 2005, it was recorded that

approximately 540,000 individuals in the United States were missing some portion of their upper-limb, with about 500 thousand of them living with the absence of one or more digits specifically [9]. In a 2014 study, it was determined that 61 percent of upper-limb amputations performed in Italy and UK are transcarpal, meaning an amputation through the finger(s) [4].

1.3 TYPES OF UPPER LIMB PROSTHETICS

The wide variety of prosthetic options can be classified first by their intended use and then by the source of power. It is worth mentioning at the start that to date no one prosthetic method or solution has been determined to be the most useful across the board, and research has indicated that prosthetic users prefer different kinds for different situations [10]. In addition, it is not uncommon for individuals to be fitted with more than one type to use as they see fit.



Figure 1.2: Upper Limb Prosthetic Examples [11]

1.3.1 ARTICULATION METHOD

The first distinction is whether the device is passive or articulating. A passive hand is set in one position and does not feature controllable joints, whereas articulating joints are capable of additional motion.

Passive prosthetics are lightweight, realistic in appearance, and can be fixed into a shape befitting a specific task or series of tasks [12]. In addition, these prosthetics share a use with virtually any upper limb addition in that they can be used to push objects across surfaces or hold

objects against the body; the major distinction is that passive prosthetics cannot complete grasping motions.

Articulating prosthetics allow for more complex interactions with at least some kind of active grasp, but can vary wildly in appearance including realistic hands, split hooks, or three-digit designs [12].

1.3.2 SOURCE OF POWER

Of the articulating prosthetics, the largest distinction is whether the motion is powered by the wearer's body, or whether an external source is involved.

Externally powered (EP) prosthetics are the most complicated kind, and involve the most components out of any prosthetic system. These designs must account for power storage, which is often in the form of a battery, transmission method, which could include electricity, hydraulics or even pneumatics, and control method, which could include physical buttons or sensors, which pick up neural or myoelectric signals from the body [4, 12]. The main advantages of an EP system are that the wearers are spared from having to power the hand's motion with their other muscles, and as such are not limited by the current max force output of those muscles [13]. In addition, electronic circuitry and sensors can allow for sophisticated actions, and potentially could allow for a more complete integration with the nervous system as technology continues to advance. However, most commercially available EP hands have been found to be heavy, simplistic, expensive, difficult to learn/maintain, noisy, and heat-trapping [4, 6, 10, 13-14]. In addition, many EP systems lack some kind of physical feedback system indicating degree of hand motion, resulting in the user having to visually monitor hand interactions in order to employ the appropriate amount of force.

Body powered (BP) prosthetics generally utilize force generated by joints and muscles closest to the absence, and involve a brace or harness attached to a cable. The benefits of a BP

system are that they are generally cheaper, lighter, simpler, more durable, easier to learn than EP counterparts [10, 12]. In addition, there is an inherent feedback in terms of the proportion of strength used to cause a specific degree of motion [10, 12]. The disadvantages of BP systems include force output being limited by the user's strength/endurance, control being limited to one direction (either to close or open the hand), and that the wearer often must counter resistances and friction from cosmetic gloves, springs, elastics, or different joint types [4, 12, 15-16].

1.3.3 DIRECTION OF VOLUNTARY MOTION

A BP prosthetic's direction of motion has to do with whether the grasping force is used to cause the hand to open, close, or move in either direction. If force is utilized in only one direction, it is named either a voluntary open (VO) or voluntary close (VC) prosthetic, and includes a restorative mechanism such as a spring or elastic to return the hand its default position. Studies of the two types have demonstrated that each direction is suitable for different applications due to differences in control and force application on grasped objects [17].

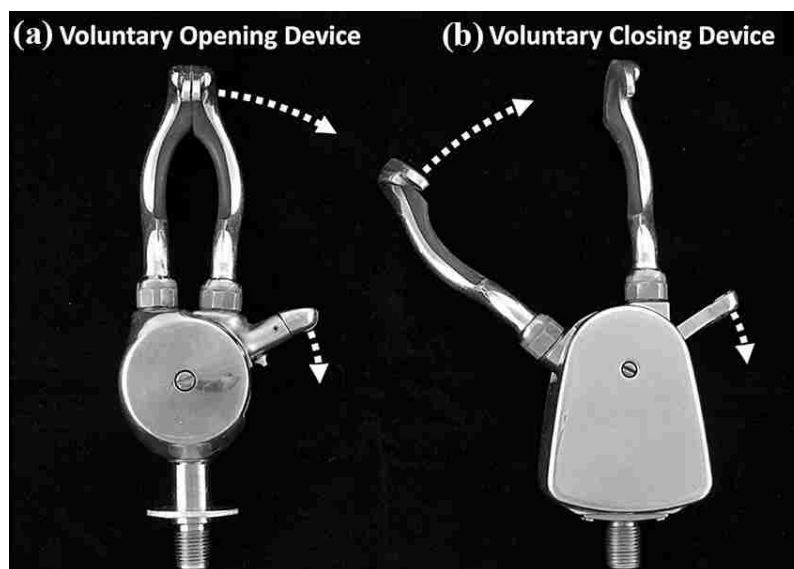


Figure 1.3: Difference Between VO and VC Prosthetic Motion [18]

VO hands, where the hand is closed at rest and force is exerted to open it, are the most common upper-limb prosthetic [15-16]. The pinching or closing force is usually a constant value, and the user is responsible for determining how wide to open the hand and whether the closing force is appropriate for each application. This setup is ideal for tasks requiring precision, viewing, or grasping for an extended period [15]. The weakness of this setup is that the closing tension may not be suitable for all objects, and that a certain degree of force may need to be exerted to resist the closing force, reducing the pressure on delicate objects [15, 19].

VC prosthetics are open by default, and require force to close around an object. Research has indicated that this method has a lot of potential, however poor application in early designs may have decreased its popularity [16]. The method provides the benefit of allowing the wearer to control how much grasp force to use, and as such has the most intuitive feedback system. Generally, VC systems are preferred for applications requiring pinching and pulling, as well as for holding larger objects [16-17]. The disadvantages of this method, however, are that a prolonged grasp requires the constant expenditure of energy and users have commented that an open resting position appears less natural [16].

1.4 THE NEED FOR IMPROVEMENT

Although prosthetics have been utilized by humans for thousands of years, and despite technological advances, the consensus is that the array of commercially available prosthetics does not adequately compensate for the absence of a limb or digit [4]. To make matters worse, not only are devices in need of improvement, it has been demonstrated that the performance of commercially available devices has remained essentially the same for a significant period of time.

1.4.1 DEVICE DISSATISFACTION

Modern prosthetics have been described as poor in both areas of functionality as well as controllability, and the result is that many individuals are not using their devices as intended [6, 20-22]. One study indicated that of a population of individuals fitted with an upper limb prosthetic, 27 percent did not actively use their device and 20 percent had stopped wearing it entirely [20]. Another study involved prosthetics users with employment, and discovered that as many as one third of them choose not to wear their device at the workplace [13].

A positive side to the situation however, is that it seems that most of the dissatisfied individuals are still hopeful that improved products will emerge. In two surveys of individuals who had rejected their prosthetic device, about 70 percent of each group indicated that they would reconsider if advancements were made available at a reasonable cost [14, 23]. If available prosthetics were to improve sufficiently, it is likely that both use and retention would increase [4]. In addition, appropriate prosthetic availability has been positively correlated with individuals entering or returning to the workplace after an accident [13].

1.4.2 LACK OF COMMERCIAL IMPROVEMENT

To provide some context to the overall stagnation of prosthetics, it is important to note that the general design methodology found in BP prosthetics can be traced to the 1950's. At that time, prosthetics were developed or modified to help soldiers returning from World War II – however many design elements have essentially remained unchanged since then [19]. Not only have devices remained similar in concept, studies and performance tests have indicated that the performance of a selection of available prosthetics has not improved significantly over the last few decades [6, 20, 24].

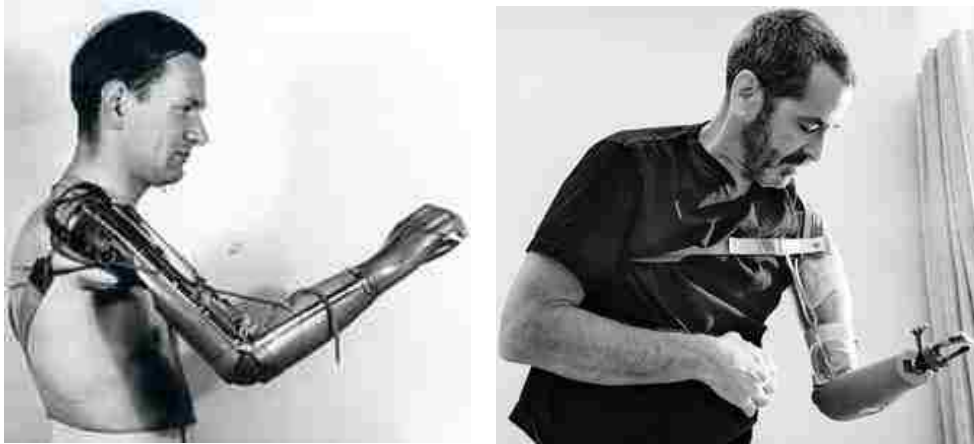


Figure 1.4: Prosthetics from the 1950's and Present Day [25-26]

In the light of this apparent lack, it is important to note that a plethora of designs and concepts have been tested in different labs around the world - indicating that there is interest among scientists and engineers to test new concepts and advance the field. One possible conclusion is that not only do prosthetics themselves need to improve, perhaps improvements could be made to the research and development process as well to better allow innovation to influence the state of the art.

1.4.3 USER PRIORITIES AND IDENTIFIED PROBLEMS

Before starting the process of improving upper limb prosthetics, it is important to find out what a prosthetic wearer is looking for in a device, and what problems have been identified. It is also worth noting that although there are many areas of consensus, individuals may have different specific priorities and/or may have different preferences regarding which device to use in their required activities.

When asked about what they value most in a prosthesis, affected individuals usually include some arrangement of appearance, cost, function, ease of use, comfort, and/or weight [14, 16, 20-21, 27]. These are often included as base objectives for new research projects, and a common problem is that any new design attempt must rank on average at least as well as

conventional hands, to make any individual change worthwhile [28]. In times where a design falls short, however, test participants have been known to demonstrate appreciation for the effort and initiative to develop new options [29].

Among the other circumstances where priorities are not sufficiently met, the main cause of prosthetic disuse or misuse is the inability to properly manipulate objects. In fact, it is not uncommon for individuals to use their intact hand (if present) to push objects into their prosthetic hand, or even to treat their hand as a passive device and use it to hold objects against their body [16]. Some individuals have even chosen to permanently turn their articulating device into a passive device by disconnecting the main cable [13]. In all such cases, the wearers demonstrate a lack of confidence in their prosthetic as a functional replacement, and can end up following one of two choices: spending time consciously overcoming deficiencies in their device, or cutting their losses by either simplify their device or choosing to go without it.

1.5 THESIS OBJECTIVES

One thing that is apparent from current research is that there is no one upper-limb prosthetic that adequately fulfills its purpose, and in addition, one person's desires may be very distinct from another's [30]. In simplest terms, the objective of the research described is to demonstrate three principles: that a modular approach to upper limb prosthetics could improve both prosthetic research as well as available products, that 3D printing can be implemented to test and produce effective upper limb devices and prototypes that can benefit a wider number of current and future prosthetic wearers, and that simple modifications can lead to an improved and customized user experience.

This research will focus on BP upper limb prosthetics for individuals who are missing some portion of their hand, but still have use of their wrist joint and musculature, as it was apparent that

such cases are the most prevalent. In addition, principles described in this research can be extended to other forms of upper limb prosthetics, both BP and EP, and may prove beneficial to devices used on other areas of the body as well. The ultimate intent is to demonstrate a novel approach to testing as well as building prosthetics, so that research can progress more quickly, and that patients can receive a hand that has the qualities that will best benefit their lives.

1.5.1 THE MODULAR APPROACH

It is proposed here, that the problem with modern upper limb prosthetics lies not only with the devices themselves, but also with the current mindset found in prosthetic research. Of course, various functional improvements will be tested and compared in this research, however it became clear when conducting a review of applicable literature that many ideas have been proven to be beneficial without making it into mainstream production. A common occurrence is that individual research groups will set goals, produce and develop a unique design, and test it in labs against commercially available products. Some of those products will end up being moved forward to comparative testing by prosthetic wearers where they may be favorably demonstrated in some areas, however the improvements are insufficient to yield a net improvement over their current device or to warrant commercial implementation.

Regardless of where a design is stopped in development, it can be said that a major err in prosthetics research as a whole has been the improper elimination of variables. When the validity of any one idea or concept is tested on a unique hand, and separate hand designs are used for comparison, the other differences between them could be numerous even if certain elements are similar. These differences could include materials, joint methods, directional resistors, cabling systems, direction of motion, number and type of digits, application of cosmetic gloves, as well as overall shape and dimensioning. Instead, it is suggested that a modular approach, where individual

hands are made capable of accepting multiple configurations, is the ideal way to demonstrate the efficacy of different hand designs, as well as different improvement principles and setups.

The adoption of modularity could facilitate the testing and efficacy of different ideas on their own merit, and could also result in more customized solutions that are both appealing and useful, and ultimately more satisfying for the wearer.

1.5.2 3D PRINTING

Two primary reasons why 3D printed prosthetics are immediately appealing, are that they are comparatively both cheaper and lighter than devices manufactured by most other means. Regular prosthetics can cost thousands to tens of thousands of dollars, and may require maintenance, repair, or replacement from time to time – a situation that is certainly not ideal for those without sufficient funds or insurance. Children are certainly at a disadvantage, as bodily growth could result in them needing multiple devices over the course of their lives. A more affordable solution could significantly increase the number of individuals who could receive help, including children, families with lower income, and residents of third world countries [8]. One of the reasons 3D printing is inexpensive and internationally applicable, is that the requisite materials are found almost anywhere in the world, and various types of 3D printers – even ones which can print in more than one material at once – are becoming even more prevalent [31].

Another compelling motivation to use the 3D printing platform is the rapid transition from conceptualization to development. Instead of having to pass through long design, and prototyping phases prior to production, different iterations and improvements can be implemented as needed. Although 3D printed designs are often not as robust or complex as professionally created hands, they are an ideal platform for rapidly testing new ideas and for producing new models as designs change, or as older models are outgrown [8, 31]. The element of quicker development and

availability may also help reduce rejection rates in and of itself; studies have shown a correlation between increased time between amputation and fitting, and lessened use and satisfaction with provided devices [17].

One caveat that should be mentioned is that 3D printed designs are often initiated or modified by lay individuals, so they may lack the efficiency, accuracy, and/or aesthetic beauty of a professionally (and more expensively) rendered prosthetic [31]. If this medium becomes more prevalent it is likely that more open-source options will become available, and the gap between the two may narrow considerably.

1.5.3 FUNCTIONAL CHANGES

With the introduction of a modular setup to the basic hand design, it became possible to test various concepts independently. Considering that a primary cause of device rejection was the inability to properly interact with objects, the primary upgrades that were investigated were ones which would help with grip and overall functionality. The three areas that were selected were: increasing max grip force, allowing for adaptive grasp, and modifying the direction of voluntary motion.

1.5.3.1 GRIP FORCE

Regardless of which system is in use, if an individual is unable to maintain sufficient grip force with their prosthetic to successfully grasp an object, the object will not be held stably and the operation will not appear natural [16, 32]. Aside from design inefficiencies, the inability to generate force could come from one of two ways: it could be the result of the muscular limitations of the user, or it could come from a range of motion that is too small to close and tighten around an object.

In cases where the user has more room for motion than needed (such as with certain shoulder or elbow harness configurations) mechanical advantage pulleys which lower the force load on the user have been demonstrated to allow for a higher force output at the expense of a larger motion requirement.

The wrist joint does not have the luxury of available room, and it is possible that a user will need the hand to move at a faster rate per angle of wrist motion accomplished. This can be achieved with what is known as low mechanical advantage, or mechanical advantage less than one. In addition to allowing a VC system to close faster, it is surmised that low mechanical advantage could also be used to allow a VO device to open wider, and more easily accommodate large objects.

Such a modification would result in a greater potential requirement on the user, but likely also would yield a more responsive prosthetic in these applications. It also serves as a proof of concept for varying the relationship between physical motion and degree of prosthetic response, as the pulley could easily be reconfigured to provide a mechanical advantage above one instead – as needed.

1.5.3.2 ADAPTIVE GRASP

One major failing of traditional prosthetic systems, is that all digits move at the same rate, and motion stops as soon as contact is made. In addition to producing an unnatural looking grip, it also results in only two to three points of contact, and requires a high degree of grip force to provide the necessary friction and pressure [6, 16, 22, 28]. A means of improving grip passively – or without requiring additional thought or effort by the wearer – is through the addition of adaptive grasp functionality.

Adaptive grasp refers to mechanisms which allow the fingers to passively encircle the object independent of each other; often through equalization of forces or tensions between digits. This leads to more points of contact and the ability to interact with a wider variety of shapes and surface types, all the while lowering the force requirements [6, 16]. Since the hand is moldable, it could allow for more potential approaches to the same object that could result in a successful grasp, reducing mental involvement when attempting to grasp an object [33]. In addition, adaptive digit motion provides a more natural looking grasp which could lead to less outside attention being drawn to the prosthesis [16, 30, 32].



Figure 1.5: Grasp Adaptation and Object Encirclement [6]

These mechanisms also help to maximize efficiency of each digit individually. Studies have shown that traditional devices grip at 92 percent efficiency without the pinky finger, and at 79 percent efficiency without the ring finger, indicating that the most work is carried out by the thumb and the first two digits [32]. This is a key reason why quite a few designs involve a passive third and fourth finger, or why some have omitted them entirely [34-35]. When each digit bears a proportional amount of the grip force load, the wear and tear is more equally balanced and longevity is improved as an added benefit [16].

1.5.3.3 DIRECTION OF VOLUNTARY MOTION

The direction which a prosthetic hand moves when acted upon, whether VO or VC, results in a device which is better suited for different tasks. Previous researchers have attempted to modify each system independently of the other, by attempting to combat the specific weakness of each. The largest weakness of VO systems is that they possess a set compressive force that may not be suitable for all tasks, so attempts have been made to implement a variable tension system that could change the closing force based on the situation [19, 21]. VC systems have the downside of requiring a sustained grip force for prolonged grasps that can prove tiresome. To combat this problem, tension lock systems have been tested which could fix the hand in position around an object without requiring the wearer's continued engagement [21]. If a device could be developed that could open and close equally well, it is possible that individuals would be able to avoid sacrificing efficiency or switching devices between tasks.

Although it remains to be proven, the wrist location may allow for bi-directional motion, one which utilizes both the flexion and extension of the wrist joint. Currently wrist-powered prostheses are powered by flexion, which results in an unnatural bent position for full grips, and has a resting open position. A hybrid system has been conceptualized that has a mostly closed position when flat, allows for further tightening with a flex motion, and allows for opening and object approach when extended. This also is closer to what is most natural and effective for the human hand. Sources indicate that the hand rests comfortably and achieves its strongest grip at a posture that is lifted or extended about 35 degrees [36]. It makes more sense then, to utilize the wrists extended posture as well, instead of relying solely on flexion.

The key determinant here, will be the ability to demonstrate that this hybrid position performs at least as well as the VC default, if not better.

2. LITERATURE REVIEW

Although quite a bit of research has been conducted to the end of developing improved prosthetics, some halting factors have prevented these improvements from reaching and improving commercial products. It has been posited that a major problem has been an emphasis on developing improved products, rather than testing the merit of the improvements using proper scientific method.

For these reasons, the research and particularly the literature review presented here may differ from the norm, in that the intent is not necessarily to prove the uniqueness of each and every idea. Instead, the purpose is to prove that certain ideas are worth revisiting or revising, especially when combined in novel ways. Below is a collection of related material that support the merit of the individual design objectives, found both among both BP and EP designs.

2.1 MODULARITY

The merits of implementing a modular system were encouraged by the development and testing of the Edinburg modular arm system. The team's primary goal was to produce a system with adaptable components that could be used to create hands that could serve a wide variety of patient groups. Prior to this project, the group had been working with externally powered limbs with differing power regimes, where each had distinct weights and capabilities. This may have acted as inspiration to adapt their components to act as a partial hand system to a full arm system, and for them to develop solutions suitable for affected individuals from four years old to adults [37].

Although the research group had a different specific focus, their work effectively demonstrated that an interchangeable system could be utilized to produce (and thereby test) specific outcomes, and increase hand customizability. In addition, their variance of application

from partial hand to full arm gives support for potential future work, of finding ways to adapt various 3D printed hands to encompass a wider variety of upper limb absence.

2.2 3D PRINTING

Considering that 3D printing has become more prevalent in recent history, little research has been done on 3D printed prosthetics. To make up for this, projects will be described which implemented hands that shared characteristics with a printed prosthetic, or which described the merits of a printed hand in general.

One of the most unique systems that added support to the idea of lightweight materials being applicable to prosthetics was the group responsible for researching endoskeletal prosthetics. The term endoskeletal, as it applies to a prosthetic, refers to an embedded rigid structure within soft supporting material, much like human bones are surrounded by muscle and tissue. This system involves plastic digits, surrounded by a soft flexible foam, which eliminated the need for joint mechanisms or a glove. The team also implemented a passive thumb that could be repositioned. In addition, the hand was relatively less expensive to produce than conventional alternatives, and was replaceable in the case of growth or damage [38]. One potential downside is that the hand appears hard to repair if something happens to one of the strings, as it may not always be practical to acquire a completely new hand.

One 3D printed hand which has been detailed and described in a publication, is the Cyborg Beast. It is a functional and low-cost alternative, and their emphasis is being able to help at a distance. The way they can accomplish this, is by having a setup that can be modified per a person's measurements. In addition, they have produced a scale that tracks the standard hand scale that the average child would use at different ages, which could be followed for future prints. Their studies have indicated that long distance interaction is not a barrier to developing an appropriately sized

prosthetic, and demonstrate how individuals could be benefited, even if they lived some distance from the source [8]. These conclusions lend weight to the idea that a low-cost, customizable hand could be printed for a wider variety of individuals, even if they live remotely, and that it can be used to accommodate the growth of a child.

2.3 GRIP FORCE

The idea was mentioned previously that any application which would increase the force required by the user is often counter-intuitive, even if it results in more prosthetic motion. As such, it is incredibly unlikely that even few, if any at all, have attempted research that utilized low mechanical advantage to do so. Instead, research which has attempted the opposite, to implement high mechanical advantage to lower force requirements have been gathered. This is to demonstrate that it is possible to modify the relationship between user input and device output to produce a specified result. In addition, the research located involves a different joint, so the physical capabilities and needs are different.

One related research group implemented a variable mechanical advantage system in their VC hand in order to reduce the physical strain of maintaining a grip on an object, while requiring more cable motion drawn. The researchers involved acknowledged that one of the difficulties behind a VC system, is that muscles must continually be engaged when holding on to an object for an extended period, but perhaps didn't feel that normal short interactions were overly strenuous. Another scenario where the advantage would be switched off is when interacting with soft objects, as low force is required by the device, and a large distance is required to accommodate sufficient deformation to successfully grip the object. Even though the idea is ingenious, the groups ultimate evaluation was that further research and testing would need to be conducted to determine if the advantages were worth the complexity and cost of development [39].

Another project was a touch more specific in application, and was referred to as an arm force reducer. In this case, a farmer with a BP VO prosthetic fitted with a shoulder holster, requested the ability to increase the maximum grip strength of his device while lowering the input force requirement to do so. In this case, the device had extra motion room that it was capable in the shoulder, which could be used to lower the amount of force increase per distance of body motion. The project ultimately achieved the goal of reducing force input, and although grip force is not something that can be increased in simple VO systems, it is possible that they were referring to the ability to open wider and accommodate wider objects. The adaptation was sent to be produced for this individual by an outside source, but ended up being more expensive than the farmer's previous device [40].

Considering that high mechanical advantage has been shown to be beneficial for systems that can accommodate the required extra motion, it is worthwhile noting that an additional config for higher advantage can be added once the hand has been modified to be powered by joints other than the wrist.

2.4 ADAPTIVE GRASP

Adaptive grasp mechanisms are systems which allow digits to passively contour around an object, and increase overall grasp efficiency, decrease force requirements, and improve overall grasp appearance (among other benefits). For these reasons, it is not surprising that this enhancement has been included in a vast variety of designs, although the exact mechanical means can be quite diverse. For the sake of simplicity, the various designs will be presented by method, with numerous groups implementing pulleys, springs, or force-distributing bars/plates, and individual groups using gears or hydraulics.

Pulleys make an ideal means of force distribution of forces, in that they are associated with low friction and do not take up much space. The general mechanism behind a pulley system is that when one digit encounters the object it stops, and the slack is transferred to remaining fingers until all digits have made contact (if possible) and tension has equalized between all digits and groups. One research team implemented a complex set of pulleys within the palm of their device, which involved force equalization between the first and second and second and third digit, between the two sets of digits combined, and between the four fingers combined and the thumb. Although this design showed some promise, this attempt was described just after the design phase, so actual test results were not presented [41]. Another group successfully demonstrated the efficacy of pulleys in an unconventional way – on a human cadaver. The attempt was meant to test an enhancement to a tendon transfer surgery, which can be simplified as a surgery which restores control of hand motion by attaching the finger tendons to a singular muscle.

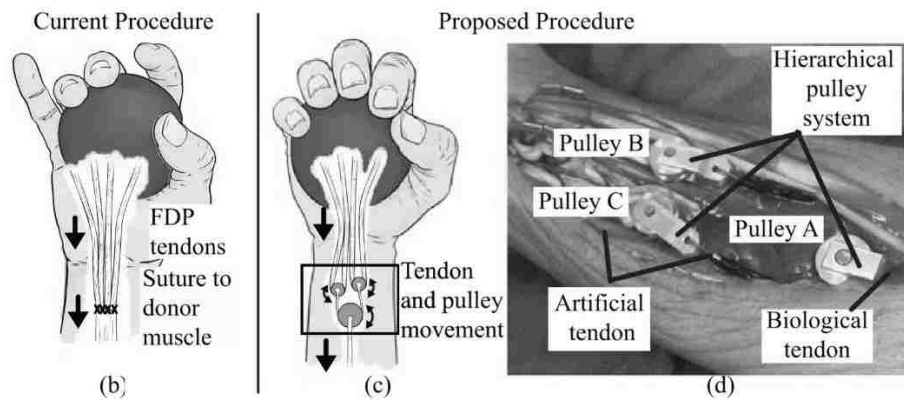


Figure 2.1: Experimental Surgery Attaching Tendons to Pulleys [32]

This was deemed similar enough to a prosthetic application, as the fingers are not able to move independently, and a muscle remote from the normal site is given power to cause motion. The pulleys were attached to the tendons within the wrist of the cadaver, and distributed forces between the first and second and third and fourth finger, as well as between the two sets. When

the modified limb was utilized for grasp testing, it was determined that the enhancement reduced the required force to pick up the object by 45 percent, and reduced slippage after contact by 52 percent (as compared to a system where all fingers were moved in unison) [32]. This can be ascribed to the increased surface area of a multi-finger grasp, as opposed to one where potentially only the thumb and first finger or two make contact.

Another method that received quite a bit of attention is one involving springs and potentially sliders. In these systems, the mechanism transfers excess tension into the springs so that each digit experiences a similar degree of force, though the individual designs varied. One design, the TBM hand, used a series of extension springs attached to an actuator to achieve their adaptation. The springs come with a pre-load, so that when the hand starts to move, they do not extend but rather just translate or slide with the pull of the cable until an object is encountered. When the first digit(s) contact the object, the extension spring is engaged for the digit(s), and the rest of the extension springs continue to slide until each makes contact as well. This system was later upgraded to another spring-related system, and it featured the common enhancement of an adjustable thumb, though theirs was not made to be passive. Although the method was innovative, there were some concerns about performance, and two papers on the design both indicated that further trial testing should be conducted [28, 33]. Another group, responsible for the RTR II design, employed a system which was a reversal of the first group. Their mechanism involved only a thumb and two fingers, and when one of the digits contacted an object, an attached compression spring absorbed tension while the others continued to move. The system also included a finger adaptation system, which allowed each segment of each digit to contact in order of most proximal to most distal, thereby possibly allowing for even more customization in the grasp (rather than each digit hinge rotating to the same degree if so constrained.) This system was ultimately

implemented in a full hand model with a concept called living hinges (to be further expounded on later), and the overall combination was described as simple but effective, however this project was also described prior to experimental testing and user trials [6, 22]. The SPRING hand was a bit of an anomaly, in that they implemented both a pulley system housed within a differential mechanism, as well as a compression springs. Like the original RTR II design, this hand employs only 3 digits which are also capable of finger adaptation. Similar to previous examples, this hand was presented in the prototype stage, though they were able to demonstrate good grasping functionality with a simplistic control through basic testing [5]. Although multiple groups may include finger adaptation, it has not been shown to contribute sufficiently to warrant mention in future work, and it is possible with a cable driven system that some finger adaptation occurs naturally.

The mechanism that most closely resembles the one to be implemented in this research is that involving a whippetree (also spelled whiffletree) mechanism, involving force transitioning between pivots on bars or plates. This mechanism can be found in scenarios such as the hitching of horses side by side to the front of a carriage— when inevitably one horse moves more quickly than another one, it would not be desirable for that carriage to turn. Instead, those horses are likely attached to a bar with a linkage in the middle, that allows the bar to pivot if the horses are not aligned, and results in a singular combined pull vector that equalizes any difference.

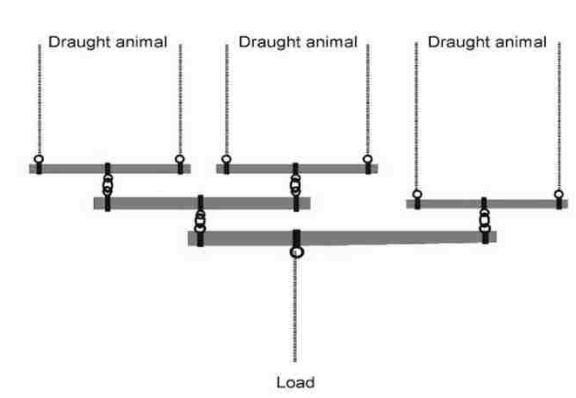


Figure 2.2: Application of a Whippetree in the Pulling of a Load [42]

In like fashion, if finger cables are attached to a bar that is pulled, a whippletree can allow slack to transition between the fingers, resulting in equal tension in each digit. One such unnamed hand design took this idea to the third dimension, by utilizing a triangular plate with a center pivot, which is capable of pivot along three different axes. This design features three actuated fingers, capable of finger adaptation, and a passive (though movable) ring and little finger. The triangular plate, in this instance, is used to equalize tension between the thumb, index, and middle finger. This design was described in the early prototype stage, though the group appeared optimistic about the appeal of increased grasp functionality [16]. The Southampton hand took the whippletree a step further, but attaching the rear of one bar to the front of one side of another bar. Similar to the successive pulleys in some designs, when one whippletree is attached to another, it can lead to force equalization between individual fingers, as well as groups of fingers. In the case of the Southampton hand, the third and fourth finger are attached to a bar, and the pivot of that bar is attached to another bar with the second finger, and the first finger is actuated independently. The reason for the separation is that this prosthetic is an EP system, otherwise it is quite likely that more force equalization bars would be utilized. This design also employed an adjustable active thumb, and performance testing demonstrated improvements in both ability to grasp objects as well as ability to perform a wider variety of tasks [30, 43].

The device that implemented a set of gears was probably the most complex. The unnamed design was described as having a multi-gear transmission mechanism housed within the palm as the means of achieving adaptive grasp, and they also featured an adjustable thumb. The mechanism employs an intricate series of planetary, sun and ring gears that cause motion to continue in the gearing/free digits until the hand has successfully conformed to the object. The feasibility of such

a design was not demonstrated, however, as the report presented it in the digital design stage, though it was indicated that a prototype was in development through a 3D printing process [44].

The use of hydraulics is unique, in that the forces related to allowing for an adaptive grasp are transmitted via the motion of fluids. The Delft Cylinder Hand was designed with hydraulic cylinders that utilizes fluid transmission to move the individual digits, but also allows for the redistribution of fluid after contact is made to allow adaptation. This group also featured an adjustable passive thumb. This method of motion and adaptation is stated to be superior to other methods in that it is light, fast, and requires less force while delivering more pinch, and performed at least equally well in functional tests to conventional hands. The influence on the grasp functionality is not elaborated, as the entire hand is focused on as an alternative to available designs; nonetheless it is still quite possible that the adaptation is a contributing factor in the lower force requirements.

It is safe to say that there is plenty of interest in a straight-forward way to include a conformable grasp to modern prosthetics, and it is the hope that in this research the benefits will be definitive.

2.5 DIRECTION OF VOLUNTARY MOTION

The last area of exploration is quite possibly the most bizarre, and is more a test of concept than a demonstration of principle. It has been established that there is no clear superior style of prosthetic in terms of VO and VC designs. Both have areas of high and low performance, and the ideal system is one which can perform well the preferred tasks of both types. The testing configuration involving direction of motion will be described in the next section, however present here is a demonstration of other research that has attempted to either enhance a VO system individually, or ones which have attempted to create a hybrid of the two.

As it turns out, it is possible that VC enhancements are sufficiently covered by either modifications of mechanical advantage or by adding a locking mechanism, and do not warrant testing outside of those areas, however research to improve a VO design was located. This concept, called the Vector Prehensor, was designed with the intent to mitigate VO prosthetic's greatest weakness, a fixed closing tension. This split-hook design featured a mechanism to easily adjust the closing force, and the adjustment was made possible by varying the position of the elastic band responsible for closing the device. When the band was perpendicular to the wrist, maximal grip force was achieved, and when one end of the band was slid to one of 13 total positions, the grip force grew successively lighter, depending on need. These changes were accomplished without significantly increasing the weight or complexity, as compared to conventional hooks, and could act as a simple augmentation for those who use such a system [19].

Rather than a prosthesis that can act as both at the same time, what all the hybrid VO/VC designs share is a method to switch from one to the other. One early attempt involved a claw-looking two-piece device with a pseudo thumb that normally acted as a VO device. When the thumb was rotated from beside the "palm" to resting over it, however, the same action would result in a VC response. The hand's original intention was to accomplish a similar action to a VO hook, but with improved aesthetics. Ultimately clinical testing demonstrated that although the cosmetic aspects were appreciated, the VC functionality remained largely unused, and the VO abilities were not superior to the wearer's default devices [29]. An attempt which came later involved a hook with a special linkage switch. When the switch was thrown, the same input force would voluntarily open or close and how it would rest when not engaged. In clinical testing, wearers of this device were either allowed to use only one of the modes, or to choose their preferred mode prior to approaching a task, and individuals in the latter group performed seven to fourteen percent better

than VC or VO limited patients. Although this study did not compare results against commercial single function VO and VC devices, it did demonstrate that a dual-purpose device could provide increased versatility to upper limb prosthetic wearers [15]. One final design is also claw-like, however it features a complex switching mechanism. Although not given a name, this prosthetic design was modeled around a commercial prehensor, and includes a mechanism featuring a geared transmission that is modified with a pull switch. The final evaluation of this design was not favorable unfortunately, and the determination was that the device was too large, heavy, and energy inefficient [17].

Although a clear solution has not yet presented itself, researchers are interested in bridging the division between VO and VC functionality, whether through enhancing each type individually or through creating a system which can assimilate both styles.

3. MATERIALS, DESIGNS AND CONFIGURATIONS

To demonstrate key essential principles, this work will focus on the capabilities of different configurations of a particular 3D printed hand. The prosthetic hand used for this study is used by individuals who retain use of their wrist joint and musculature. The 3D printed BP hand for such cases involves a series of lines or cables attached to a wrist mount or gauntlet, which extend to the fingertips. When the wrist is flexed, the path length between the fingertips and the wrist attachment point of the lines is increased, and the fingers curl. Different configurations were achieved by attaching the lines in different ways to affect the behavior of the fingers when closing around a variety of object shapes.

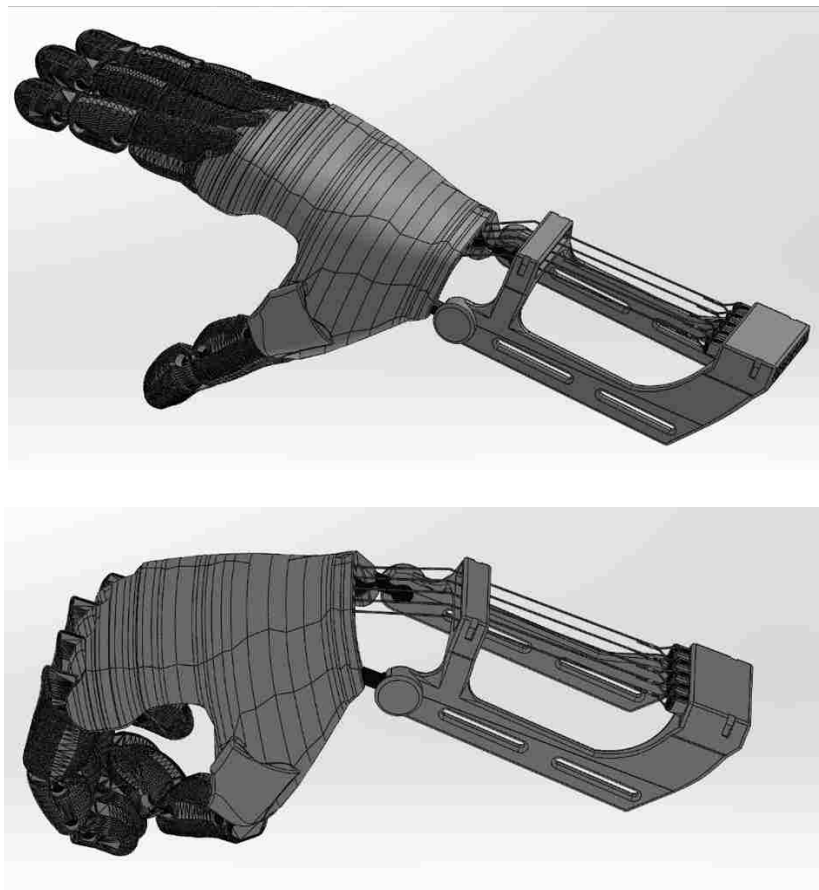


Figure 3.1: Open and Closed Positions of the Hand

3.1 PROSTHETIC HAND DESIGN AND MATERIALS

The model chosen for use in this work was a modified version of a prosthetic hand design called “Flexy-Hand 2” found on the open source project website Thingiverse [45]. The design for Flexy-Hand 2 is similar to that of another open source prosthetic hand called Robohand, and reports describing the development of each is available for further review [46-47].

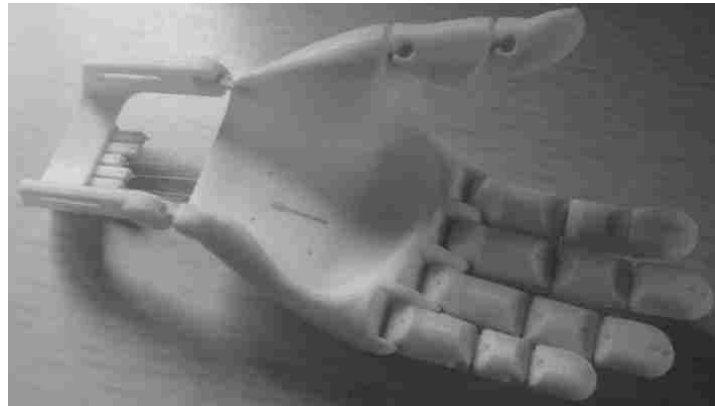


Figure 3.2: A Basic Version of the Flexy-Hand 2 [45]

The default components of this device include the palm, phalanges, gauntlet, and all related joint components, shown in Figure 3.3. The device was ideal due to its anthropomorphic design, potentially eliminating the need for a prosthetic glove or cover, and the added friction, heat, and resistance that could have provided, and increases the overall potential appeal. The rigid components are printed with ABS material on a Stratasys Fortus 250 machine. It also features living hinges for joints, which is where two segments are connected by a bendable 3D printed material called NinjaFlex® with some restorative elastic properties [22]. This eliminated the need for additional pivots, sliders, springs or elastics, and results in a simple and lightweight prosthesis. This arrangement also retains as much of the initial force as possible, without worrying about losses through unneeded complications and frictions [16]. The lines used to transfer motion to the fingers in these experiments are nylon coated fishing wire, which are fastened using crimp sleeves which are compressed using a hand crimper. Typically, the lines are fastened to the gauntlet by a

printed plastic piece called a tensioner, which rests in a channel in the gauntlet. Woodscrews are used to hold the tensioners in place, and can be tightened to increase or decrease tension in the lines.

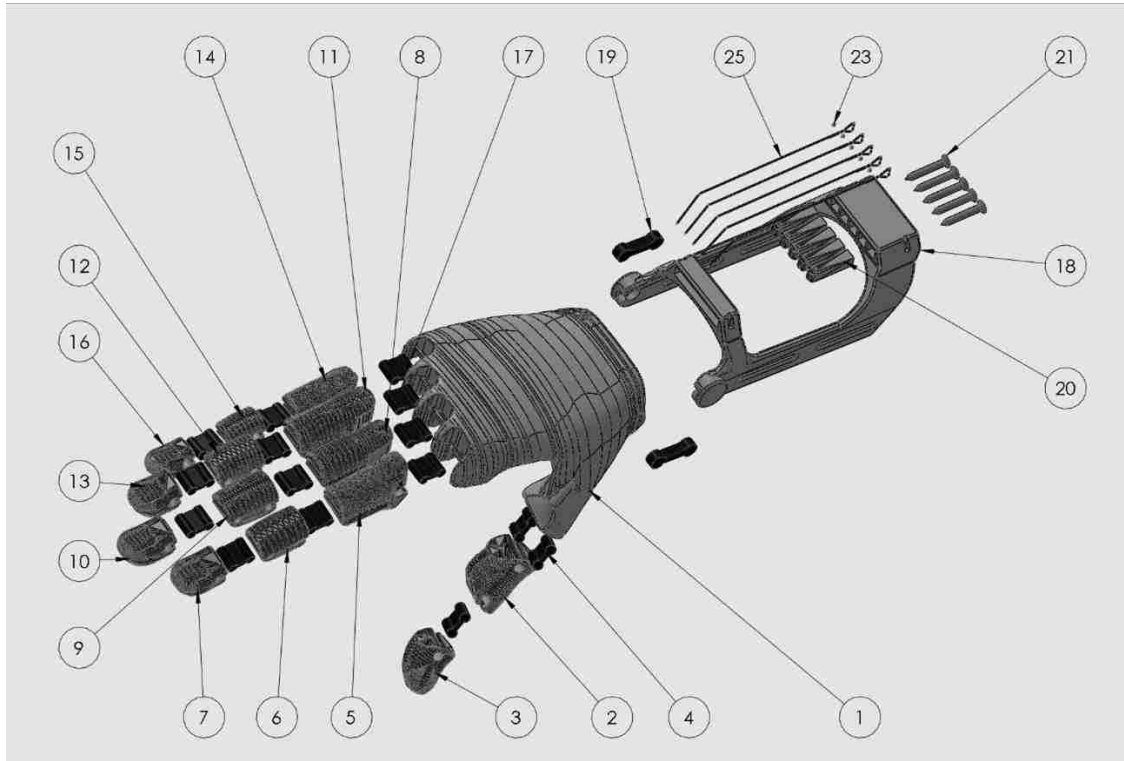


Figure 3.3: Exploded View of the Default Hand

Table 3.1: List of Materials Found in Default Hand

Item Number	Item Description & Quantity	Item Number	Item Description & Quantity
1	Modified Flexy-Hand	17	Knuckle Joint (x4)
2-3	Thumb Pieces (2)	18	Custom Gauntlet
4	Digit Joint (x11)	19	Wrist Joint
5-7	Point Finger Pieces (3)	20	Tensioner
8-10	Middle Finger Pieces (3)	21	#6 Screw (x4, between .5"-1")
11-13	Ring Finger Pieces (3)	23	Malin ® Single Sleeves (x10, .071" ID)
14-16	Little Finger Pieces (3)	25	Malin ® Malon-7 Nylon Coated Wire (x5, .026" D)

Considering that the Flexy-Hand 2 was created using Autodesk Meshmixer ®, a program that was not often utilized at UNLV, most of the design files had to be transferred over to SOLIDWORKS ® for processing before they could be edited or incorporated into assembly files.

The Hand file was too complicated, however, and had to be recreated. The fidelity of said recreation is demonstrated in Figure 3.4, where the original wireframe is highlighted in blue and overlaid on top of the design.



Figure 3.4: Flexy-Hand 2 Recreation in SOLIDWORKS ®

The palm file was then eventually modified in other projects to help improve performance. The modifications from the original came through work on other projects, and the most significant difference has to do with a re-arrangement of the thumb position to allow for better encirclement. These differences are demonstrated in Figure 3.5, shown both with and without the original design overlaid on it. The gauntlet file was generated by taking general measurements, and then creating a reproduction based off those measurements. The original palm recreation, the modified palm, the gauntlet, as well as all other files used in testing can all be downloaded online for further comparison or experimental recreation. The recommended scale for everything is the default, which is set at 100%.

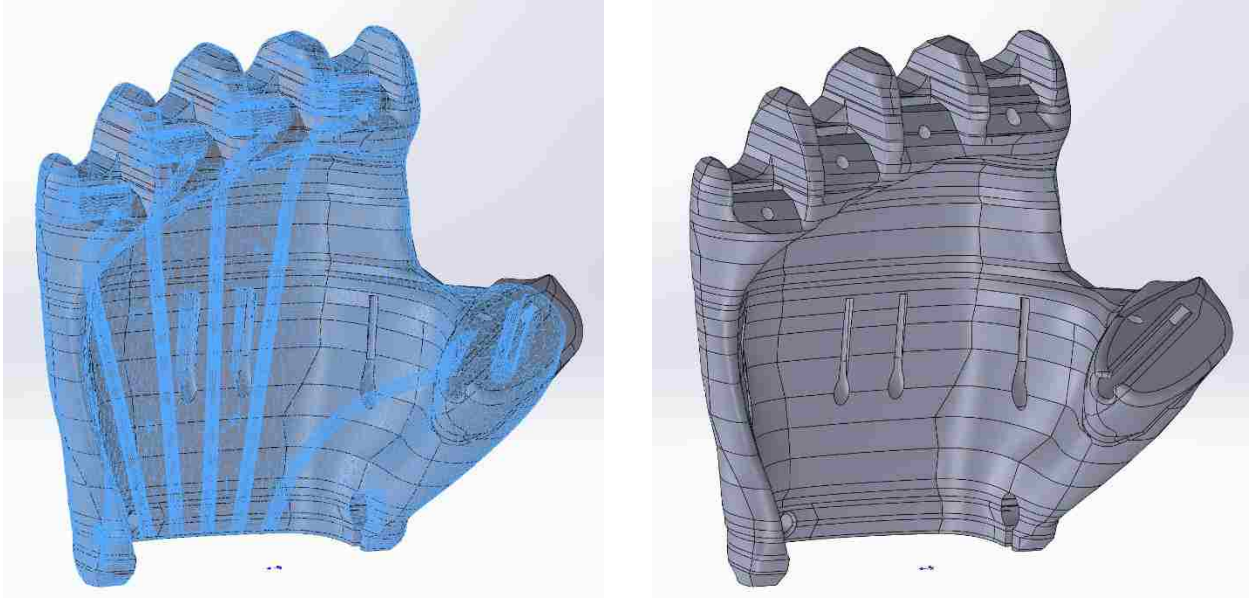


Figure 3.5: Modified Palm File with and without Original Design Overlay

3.2 METHOD AND DESIGN USED BEHIND CONFIGURATIONS

The standard setup of this particular prosthetic involves a series of long segments of line or cable on the back of the wrist, much like guitar strings. The various testing arrangement will be set up through the re-stringing of the device, and the inclusion of some custom-printed or constructed additions to the lines.

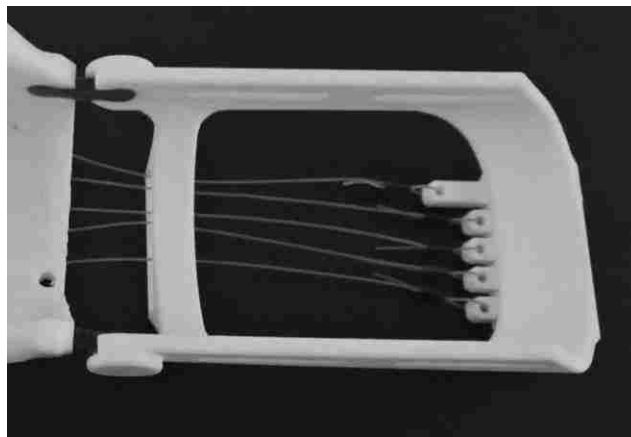


Figure 3.6: Default Cable Arrangement

3.2.1 FORCE MAGNIFICATION CONFIGURATION

To increase the force available to the user over a shorter area of space, it was devised that a mechanical advantage pulley could be placed in reverse. Normally such pulleys are used to decrease the force applied by the individual, at the expense of slower motion of the object to be acted upon and more line consumed, as shown in Figure 3.7.



Figure 3.7: Mechanical Advantage Pulley [48 – with modifications]

In the case of the prosthetic, the lifting of the object represents the action of the device, and the pulling on the string represents the corresponding physical action required by the wearer, which is induced by flexing the wrist. Such a scenario is appropriate when extra motion is available, and can result in a greater max output due to a decrease of the requirements. That luxury is not available in the wrist joint, so an implementation of the pulley in reverse, Figure 3.8, should allow for increase of motion of the object, at the expense of a greater force required by the wearer across a shorter pull distance.

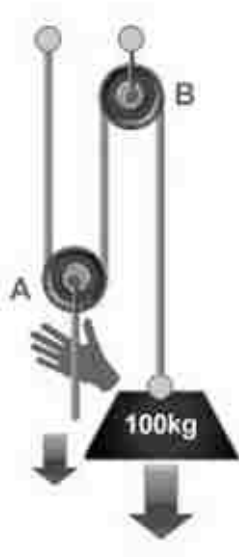
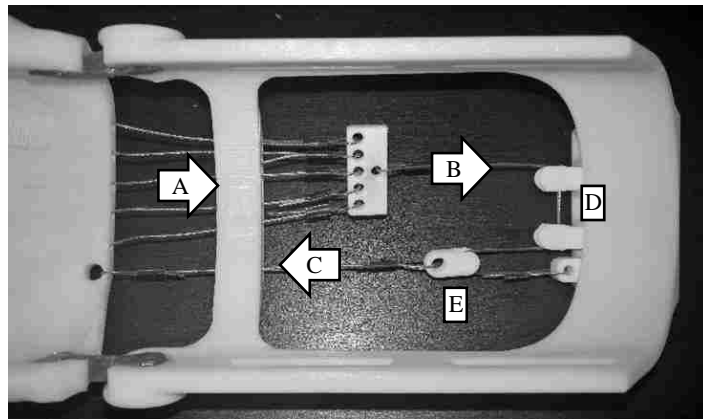


Figure 3.8: Low Mechanical Advantage Pulley [48 – with modifications]

The hope is that the benefits accrued by this modification exceed the increase in physical demands. To add the pulley to the wrist portion, the five lines had to coalesce into a single line through attachment to an object, and that line is fed through the low mechanical advantage pulley. One version of this configuration is shown in Figure 3.9 below.

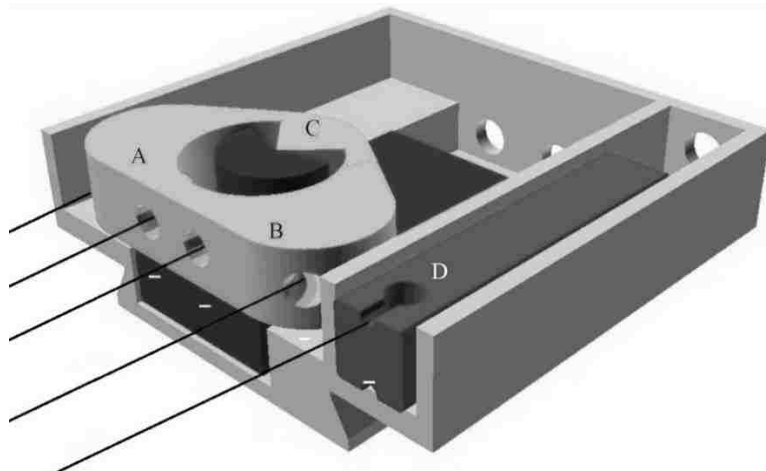


A	Normal line resistance leading to finger motion
B	Additional tension intended to increase finger motion
C	Source of additional tension
D	Rounded fixed pulleys
E	Floating pulley

Figure 3.9: Force Magnification Arrangement

3.2.2 ADAPTABLE CONFIGURATION

Various ideas were considered to add adaptive grasp functionality, but the idea that was ultimately easiest to implement came from work done by the group responsible for the 3D printed prosthetic called the Phoenixhand [49]. One of their hand modifications involves a pivot based around the whippletree principle to allow for more even distribution of tension between the fingers using the pivot and some channels that allow the line to slide, as shown in Figure 3.10.

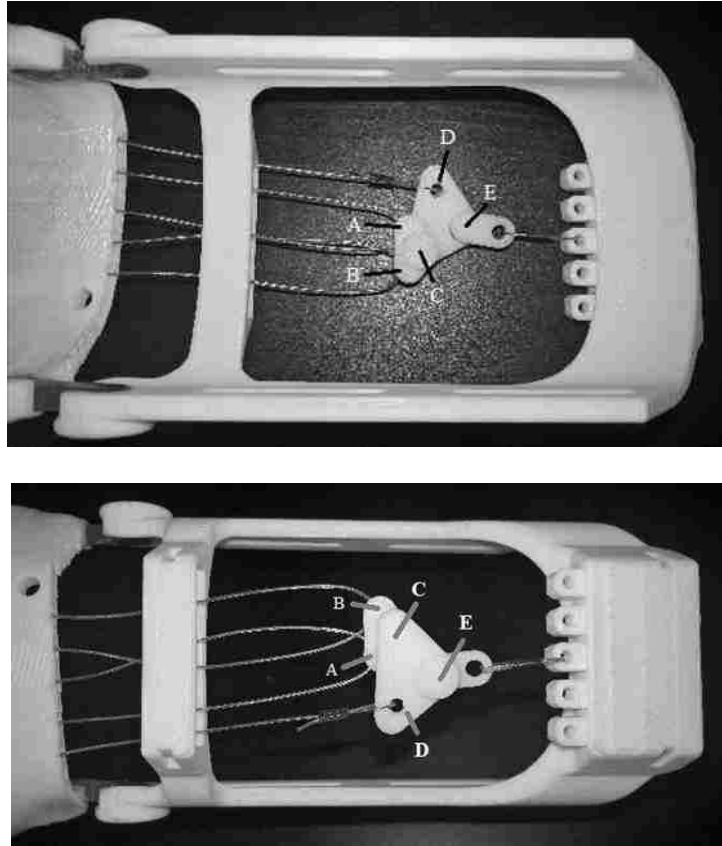


A	Sliding connection between ring and small finger
B	Sliding connection between pointer and middle finger
C	Pivot balancing tension between (A) and (B)
D	Thumb connection Point

Figure 3.10: Original Phoenix Gripper Box [49 – with modifications]

That design was modified in this study includes an additional pivot which balances force experienced by the thumb with that of the other four fingers, allowing for distribution of tension between all five digits. In all, there is one line that connects the index finger to the middle finger that passes through a slider, a line that connects the ring finger to the little finger, and a pivot between. In addition, there is yet another line that connects the thumb to one end of a pivot that balances forces between it and the four fingers. Another major difference is that the original pivot was designed to be fixed on the back of a plastic gauntlet, however it was redesigned to

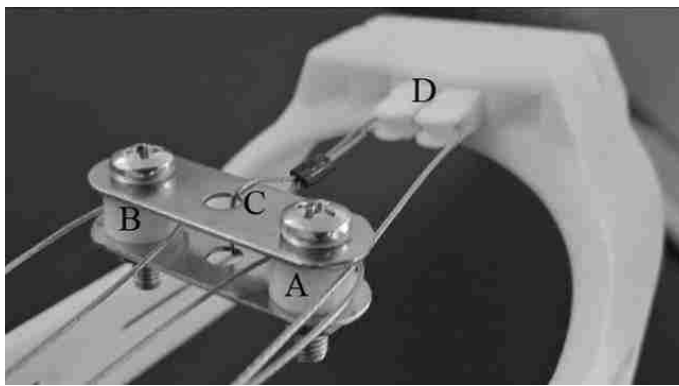
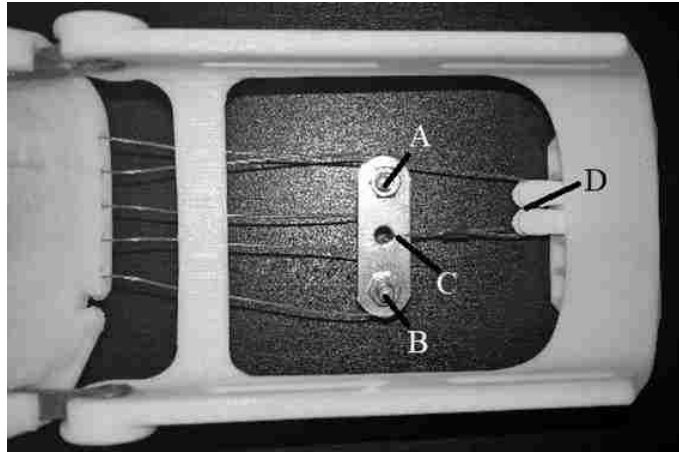
accommodate the strings used in this work. This component is available online for download and further study and can be seen in Figure 3.11.



A	Sliding connection between pointer and middle finger
B	Sliding Connection between ring and little finger
C	Pivot balancing tension between (A) and (B)
D	Thumb connection point
E	Pivot balancing tension between (C) and (D)

Figure 3.11: Lower and Upper sides of Adaptation Arrangement

Due to the small dimensions of the various parts involved in the adaptable component, it was deemed expedient to come up with a more robust alternative in the event of part failure. Rather than redesigning and printing a new 3D printed adaptation part, a custom setup was put together using screws, bolts, nylon spacers, and metal plates from a hardware store.



A	Sliding connection between point and middle finger
B	Sliding connection between ring and little finger
C	Pivoting attachment balancing tension between (A) and (B)
D	Pulleys balancing tension between (C) and thumb

Figure 3.12: Durable Replacement for Plastic Part

Instead of embedded pivots, this setup involved two loops that would allow free sliding between the two groups of fingers, a bar that could pivot off the affixed line, and a rear static pulley that would allow free motion between the thumb and four fingers. Not only is the alternative more durable, but the wider nature of the bar shape, as well as the inclusion of the rear pulleys allows for more range of motion, and therefore a higher degree of accommodation.

3.3 HYBRID ARRANGMENT

The idea for creating a hybrid arrangement came from feedback from other projects. The way most wrist-powered prosthetics work involves the flexion of the wrist joint to achieve grasp, and the flattening of the wrist to open. This results in an atypical series of motions to accomplish

basic tasks, and could very likely result in discomfort. Additionally, it has been demonstrated that the wrists natural position as well as the position of greatest power is one where the hand is slightly lifted or extended by approximately 35 degrees [36], as shown in Figure 3.13. It was hypothesized that if the hand were pre-tightened to a mostly or entirely closed position, it could potentially be opened using extension, and then flexion could still be employed to tighten the grasp. The idea of a prosthetic user lifting their hand when approaching an object and then holding it at a more neutral position could result in a much more natural looking and feeling experience, while not neglecting a position of strength. If the concept proves beneficial, the exact dynamics of the motion can be modified by varying the initial level of closure, depending on how much room is needed to successfully open and close the prosthetic.

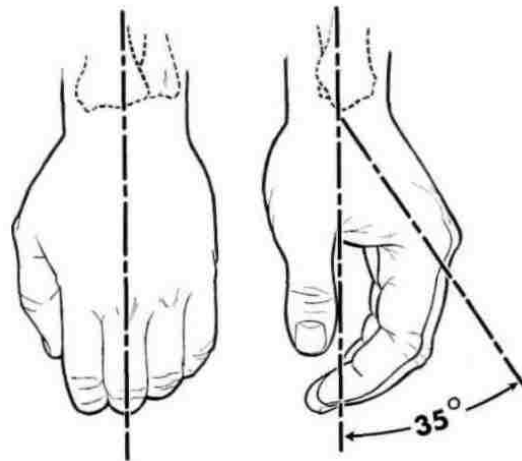


Figure 3.13: Demonstration of Hand Angle at Rest [36]

The hybrid arrangement was implemented by pressing down on the hinge of the hand until the edge of the thumb is flat on the table, thereby allowing for a consistent wrist angle to be achieved with each hybrid setup. The strings are tightened while the hinge is being pressed down as shown in Figure 3.14.



Figure 3.14: Hybrid String Arrangement

Once the strings have been tightened appropriately, the hand will return to an angle that allows for slight extension when at rest (wrist angle equal to about 20° of elevation), and at least partial finger closure when the hand is flattened (wrist angle equal to 0°). The difference in appearance between the two forms can be seen in Figure 3.15.

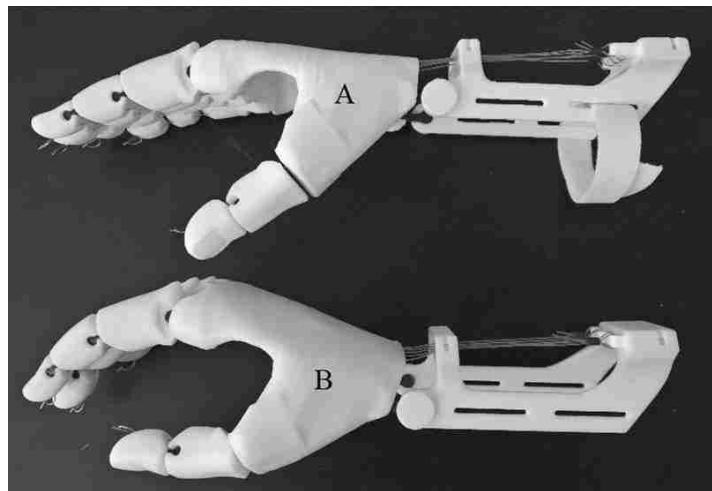


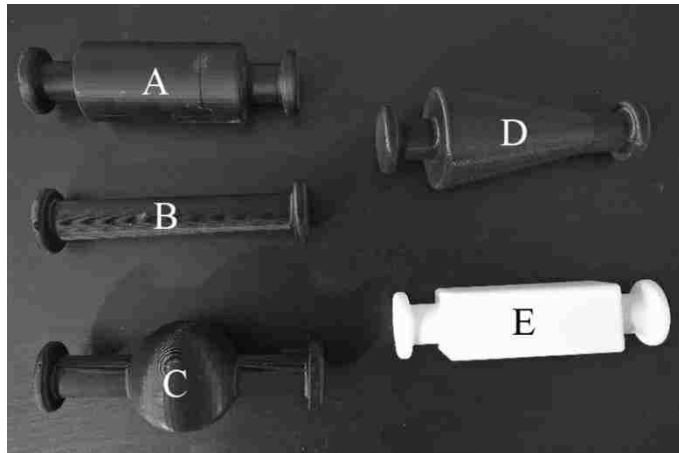
Figure 3.15: Comparison of Default (A) and Hybrid (B) Arrangements

It is important to note that the hybrid configuration can be implemented in conjunction with the default hand, or with any other setup, as it has to do with how the lines are tightened. Each configuration will be tested with the normal amount of tension, as well as with the increased initial tension described above.

3.4 SHAPES USED FOR GRIP EXPERIMENTS

As mentioned previously, the main cause of prosthetic disuse or misuse is the wearers' inability to properly manipulate objects. As such, it was determined that success could be attributed to a design which can sustain a grasp on a variety of common shapes, and do so bearing a higher amount of weight. This is most likely achieved if sufficient force is available in the grasp and that sufficient contact is made to provide friction and reduce slippage.

Considering that manual interaction has been a basis of design for almost everything that a human might interact with, a significant number of objects feature a handle, bar, or grip of some kind. Such means are a primary way of opening doors, of moving belongings, of accessing stored items, operating tools as well as many other actions. For this reason, it was decided that the medium of interaction would be bars of various shapes which would then provide a place for weighted bags to be attached. The various shapes, shown in Figure 3.16, were designed to include a rectangular prism with a square profile, cylinders with narrow, and wide diameters, another cylinder with a diameter that changes from wider to narrow (and will be tested in both directions), and one bar with a spherical shape in the middle. Each shape has been designed to have a catch on the end to prevent bag slippage. Weight will be added for each configuration with each bar until the maximum amount that can be added and held for ten seconds is determined. These bars were printed out of ABS material.



A	Wide bar
B	Narrow bar
C	Sphere-shaped bar
D	Variable width bar
E	Square profile bar

Figure 3.16: Differently Shaped Testing Bars

3.5 GRIP FORCE TESTERS

Dynamometers are instruments that are used by professionals in medical related fields to determine manual force output. They operate by digitally or hydraulically recording and signaling the maximum force a gripped fist can generate. The digital measurement will be carried out by a Camry 200 lb. (90.72 kg) digital hand dynamometer, and the hydraulic measurement will be recorded using a Baseline 12-0241 lite hydraulic hand dynamometer, also with a 200 lb. (90.72 kg) capacity. The two values will be recorded separately and averaged together.



Figure 3.17: Camry and Baseline Dynamometers [50-51]

4. EXPERIMENTAL PROCEDURES

Considering that it would be impossible to exactly replicate the performance of the prosthetic devices without an individual who is missing digits from their hand, it was decided that the experiment would be run in two different ways. The first involves the insertion of a testers hand and wrist into the device, albeit in an unconventional way, and the second involves suspending the gauntlet using a series of clamps and applying force from outside of the hand. The first setup is intended to mimic hand behavior inside of the prosthetic as best as physically possible by someone who possesses all their digits. This substitution may introduce as many differences as it does similarities, so the second setup is intended to separate bodily mechanics from the process, and focus specifically on the performance of the hands without the constraints of joint range of motion and wearer strength. Although the setups for the two testing configurations will differ, the same configurations and equipment will be used. The differences can be found in the specific testing protocol below.

Unlike the previously mentioned research, the differences between one configuration and the next will not be achieved with differing palm or finger mechanisms, but rather in different ways that the strings are arranged and manipulated in the open wrist portion, thereby facilitating a wide variety of changes.

Corresponding to the sections above, the different configurations will include a default setup with no modifications, one designed to increase grip force and responsiveness, one to allow for adaptive grasp, and one that both increases grip force as well as allowing for adaptive grasp.

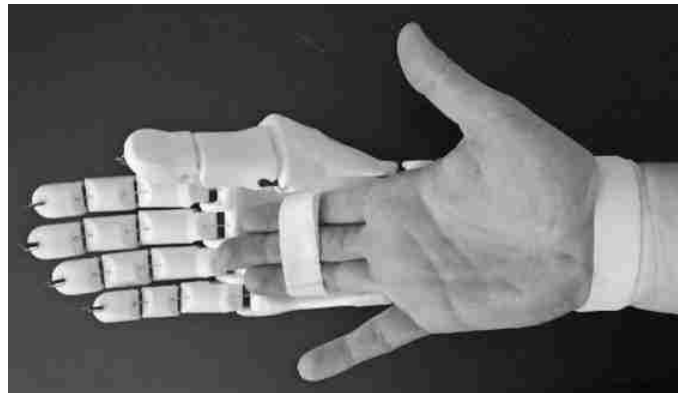
Each setup will be tested in the normal VC arrangement, side by side with a hybrid VO/VC arrangement to see what changes improve performance, and which ones hinder it.

Testing will involve grasping various shaped bars which are attached to a weighted bag, and an attempt to lift and hold on to them. The goal is to find the maximum weight each hand/shape arrangement can successfully lift and maintain aloft for 10 seconds without falling. The various configurations will also be tested for maximum force output using a dynamometer.

The testing will be conducted twice with each line arrangement, one open and one in the hybrid configuration. This means that a max weight per bar shape, and a max grip force on the dynamometer will be recorded two times per line configuration. These values will be acquired yet again once everything is arranged in the alternate test setup.

4.1 TEST SETUP ONE: USE OF A TESTER'S HAND

During the first setup of the experiment, the palm attachment will instead be attached to the tester's fingers, due to the limited space available. Actual performance may vary differ from an intended recipient of such a hand, as different joints and muscles would be used to power the motion.



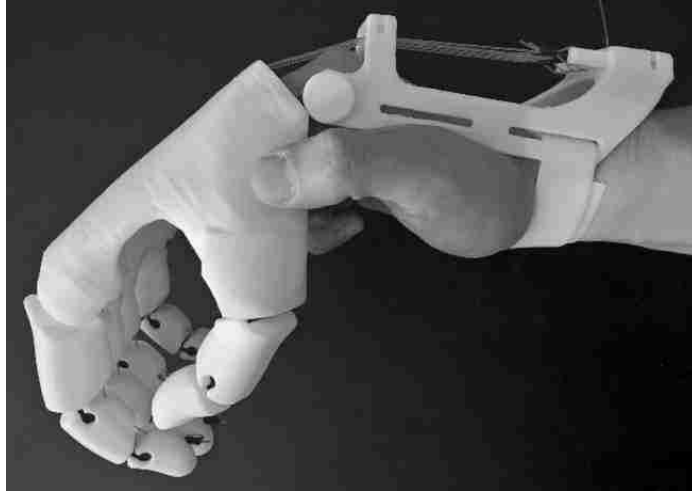


Figure 4.1: Testing Arrangement and Motion

Considering that each hand configuration is tested with each bar as well as with the dynamometer, it is important to first assemble the hand correctly prior to gathering the required materials. The first hand that is tested will be the default hand, without any additions and with tension limited so that when the hand lies flat the lines are taut. The testing bars should then be gathered, as well as a series of weights to allow for different weight combinations, as well as bags to hold them in. In this testing, 2, 3, 5, and 10 lb. (.91, 1.36, 2.27, and 4.53 kg) hand weights will be used. An initial weight should be chosen on the low end, such as 5 lb. (2.27 kg) to perform the initial test, and be placed inside of the testing bags. The bag handles are then placed over the ends of the testing bar, which should then be lifted off the floor by the testers other hand, or by a second individual. The prosthetic should then be used to encircle the bar with the device's fingers, and the bar lifted so that no part of the bag is touching the floor. Force will be exerted in order to create the maximal curvature possible with each load. It is worth noting that due to differential line tightness, and the variable effect that different loads will have on the hand, that the resultant angle between the hand and gauntlet may vary from case to case. In these tests, angular consistency during each grip will be deprioritized, in favor of making use of the angle that will allow for the

maximal load possible. In addition, the hybrid configuration exists with additional included tension, so there is a significant distinction in the two cases between wrist angle and resultant curvature, in that the hybrid setup will have a higher degree of curve per angle of motion. If the weighted bag can be sustained in the air for at least ten seconds without falling, higher weights should be chosen and tested until the weight can no longer be sustained. Each unsuccessful weight will be retested after a rest period to ensure that the grasp cannot be sustained for the time period. The narrow bar will be tested first, then the wider bar, the sphere-shaped bar, the variable width bar (with both the narrow and the wide end faced towards the thumb separately), as well as the square-profile bar, and the maximum weight will be determined for each. An example of contact between the prosthetic hand and a weight-laden bar can be found in Figure 4.2, though it is important to note that a downward wrist direction is preferable when testing, in that it allows for more of the weight to be supported.

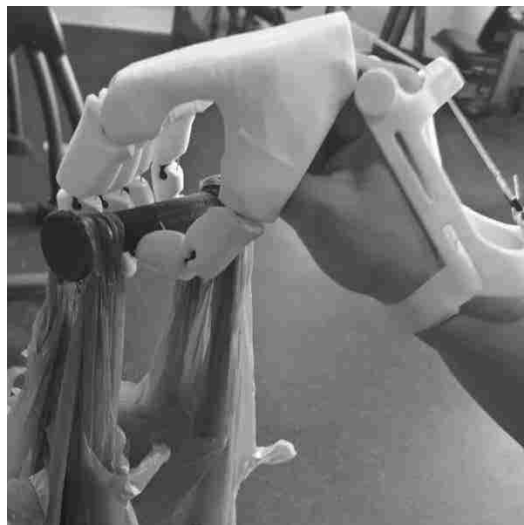


Figure 4.2: Example of Weighted Bar Interaction

When the maximum weight per bar has been determined for the current hand configuration as well as the force output on the dynamometer, the hand should then be re-assembled into the next configuration, and the test repeated.



Figure 4.3: Grip Force Measurement with a Digital Dynamometer

4.2 TEST SETUP TWO: USE OF A SUSPENDED SYSTEM

The second test setup will utilize clamps to suspend the hand and allow for grasping power to be provided externally. The clamps chosen for this distinct task are manually tightened and can be attached one to the next in series, to orient the final connection interface downward.





Figure 4.4: Clamp profile and attachment method [52-53]

The prosthetic itself will be strapped to a segment of PVC pipe with segments cut out of it to provide a better connection, and the PVC will be grasped by the downward facing clamp with a buffer material to distribute the forces across the pipe surface.

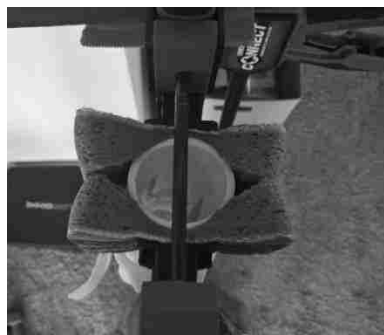


Figure 4.5: Method of Suspension Used

After the clamps have been put into place, the testing bars and weights will be gathered, and the tests will be run in the exact same order as before, with the only difference being the exact method of acquiring the test bar and powering the grasp. The tester should remember to test each of the bars with each hand configuration, as well as test force output using the dynamometer.

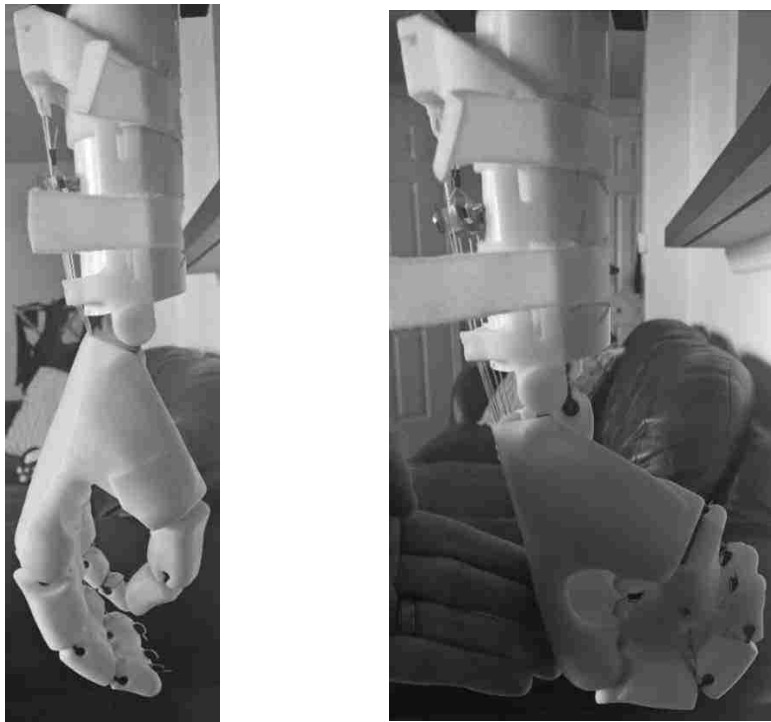


Figure 4.6: External Force Applied to Initiate Grasp

When a human attachment point is eliminated as a requirement, also eliminated are the strength and flexibility constraints provided by the individual's joints and muscles in their forearm and hand. By powering the grasp from outside of the prosthetic, larger muscle groups in the arm can be employed, and it becomes possible to potentially load the hands with higher weights if the grasp can support it.

The specific method for loading the hand, once the correct configuration, bar, and weight has been chosen, involves lifting the weighted bar into the hand and sustaining it momentarily. A free hand should then be employed to apply pressure to the hand until the bar is supported by all

five digits if possible, and the highest degree of curvature is achieved. As with test setup one, achieving the highest degree of curvature per load weight may result in a differing angle between hand and gauntlet in different scenarios. For these experiments, emphasis has been placed on bending the hand to a sufficient angle to sustain the highest possible weight. As before, the hybrid configurations also experience the added disconnect from angle in that they are assembled to have a higher degree of curvature, and therefore would have a higher amount of finger motion per degree of wrist movement. Once this has been accomplished, the tester should stop supporting the bar with their other hand, and determine whether the hand can support the weight for ten seconds or whether the weighted bar will fall. Upon failure to sustain the grasp for ten seconds, the trial will be repeated to ensure that the weight is above the grasps capacity.



Figure 4.7: Grasp Demonstration with a Loaded Bar

One difference from the first test setup that involves the dynamometer, is that the measurement will have to be taken and read upside down. Other than this, the value is obtained in the same way.



Figure 4.8: Upside Down Measurement of Grip Force using a Digital Dynamometer

One thing to keep in mind that is not quite as likely with the first test setup, is to make sure that the weight is resting entirely on the fingers, and not on protrusions within the palm. Although it may be possible to utilize the hand geometry like this in real life, it will alter test results if care is not taken while acquiring data.

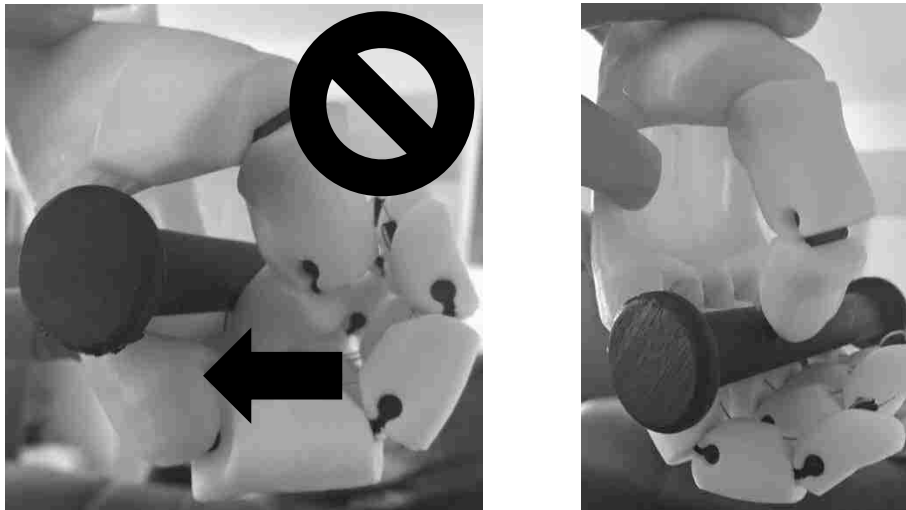


Figure 4.9: Incorrect and Correct Hand Loading Method

5. RESULTS

5.1 SETUP ONE: DEFAULT AND HYBRID DEFAULT CONFIGURATIONS

The first two hand configurations that were tested were the default, and hybrid default arrangements, or in other words, the normal configuration without initial tension and the hybrid version with initial tension. The default hand serves as the baseline, as it demonstrates how the hand could perform as it has always been assembled in the past, and serves as the basis for the other changes to be compared against. The hybrid default configuration included pre-tensioning on the fingers, which leads to a state of greater finger closure and requires a different grasping action.

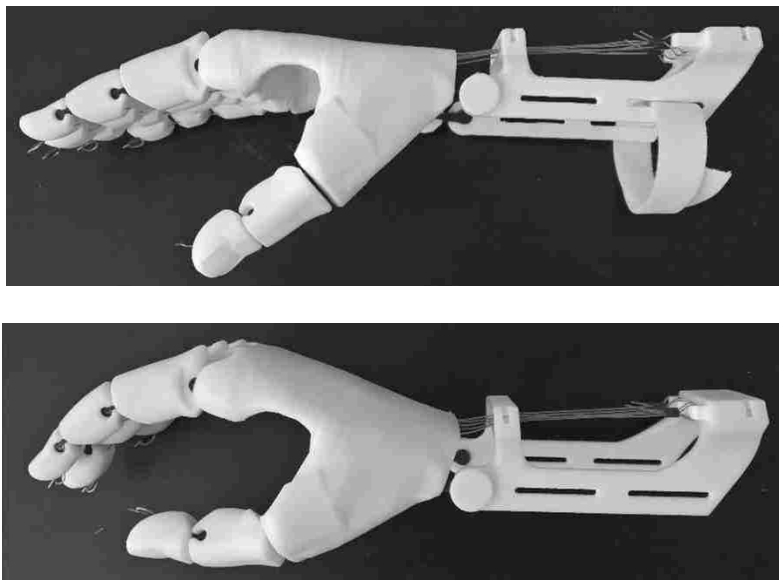


Figure 5.1: Default (above) and Hybrid Default (below) Configurations Used in Testing

Both hands were first tested on the dynamometers to determine maximum grip force. It was determined that it was unlikely for any of the configurations to be able to generate more than five pounds of force, the hydraulic dynamometer was excluded in favor of the less subjective digital instrument.

The Hands were then tested on the various bars to determine their max carry weight per shape. It was determined that the hybrid hand could generate a higher grip force on the dynamometer, and was able to sustain a higher amount of weight on each bar shape. The best performance was recorded on the bars that were uniform thickness across, namely the narrow, wide, and square profile test bars. The six different test cases (A-F) are summarized in Table 5.1. The maximum grip force and force measurements from each test case are presented in Table 5.2,

Table 5.1: Test Cases

Test A	Max weight with narrow bar
Test B	Max weight with wide bar
Test C	Max weight with sphere shaped bar
Test D	Max weight with variable width bar (wide side near thumb)
Test E	Max weight with variable width bar (narrow side near thumb)
Test F	Max weight with square profile bar

Table 5.2: Setup One Default Hand Configuration Results - Maximum Force in Each Test

Configuration	Grip Force	Test A	Test B	Test C	Test D	Test E	Test F
Default (lb.)	2.4	5	7	6	4	4	7
Default (kg.)	1.09	2.27	3.18	2.72	1.81	1.81	3.18
Hybrid Default (lb.)	3.6	13	11	9	10	10	13
Hybrid Default (kg.)	1.63	5.90	4.99	4.08	4.54	4.54	5.90

*Grip force error: +/- 1.13 lbs. or +/- 0.51 kg

5.2 SETUP ONE AND TWO: FORCE MAGNIFYING CONFIGURATIONS

The force magnifying configuration proved to be a complicated concept to demonstrate and test. When the hand was assembled with the low mechanical advantage pulley included, the parts essentially seized up, and would not move. It was then decided that if the pulley were removed, but a line was retained that would attach from the back of the hand, through the back of the gauntlet and back to the five strings, that a similar effect could be accomplished. As the wrist joint was flexed, force should be applied to the five lines leading to added tension and finger closure.

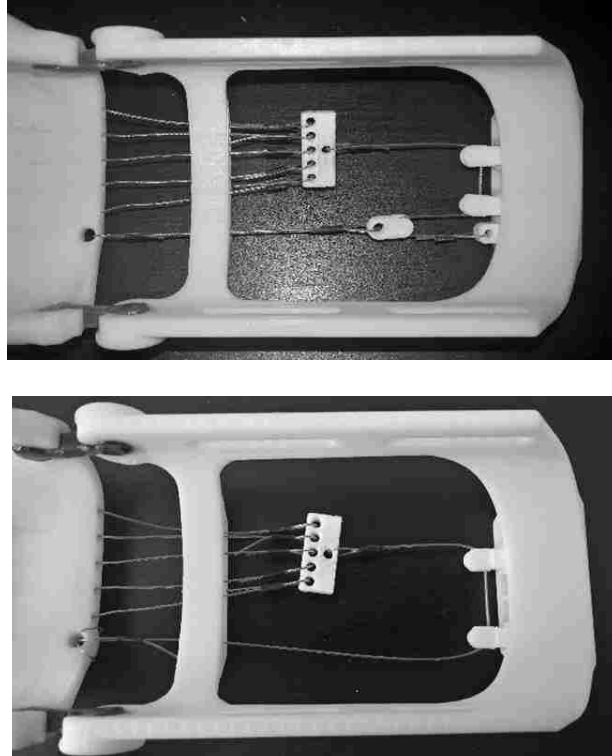


Figure 5.2: Force Magnification Arrangements with and without the Pulley.

Unfortunately, the modification did not solve the problem, and attempting to apply force to this system led to breakage in the lines. It can be presumed that instead of adding tension to help close the hand, that the line was essentially getting stuck at the back of the gauntlet, and all of the force was being applied to the stuck line without moving to other areas. It is possible that such a situation could be avoided in the future with the use of superior rotation connections in the back, rather than just round (but unmoving) plastic shapes to transfer the tension. The highest force displayed on the dynamometer prior to such a mechanical failure was 2.4 lb., which was the equivalent to the force demonstrated by the default hand. Considering that instability of the system at the time, weight testing was omitted for either test setup, as well as the possibility of adding this modification to an adaptable configuration.

5.3 SETUP ONE: ADAPTABLE AND HYBRID ADAPTABLE CONFIGURATIONS

The adaptable setup also faced some challenges. The plastic parts allowing for hand adaptation proved successful at allowing the fingers to adjust to objects, but broke during the dynamometer force test. Figure 5.2 demonstrates the level of accommodation that was possible with the plastic insert, prior to the system having to bear heavier loads.

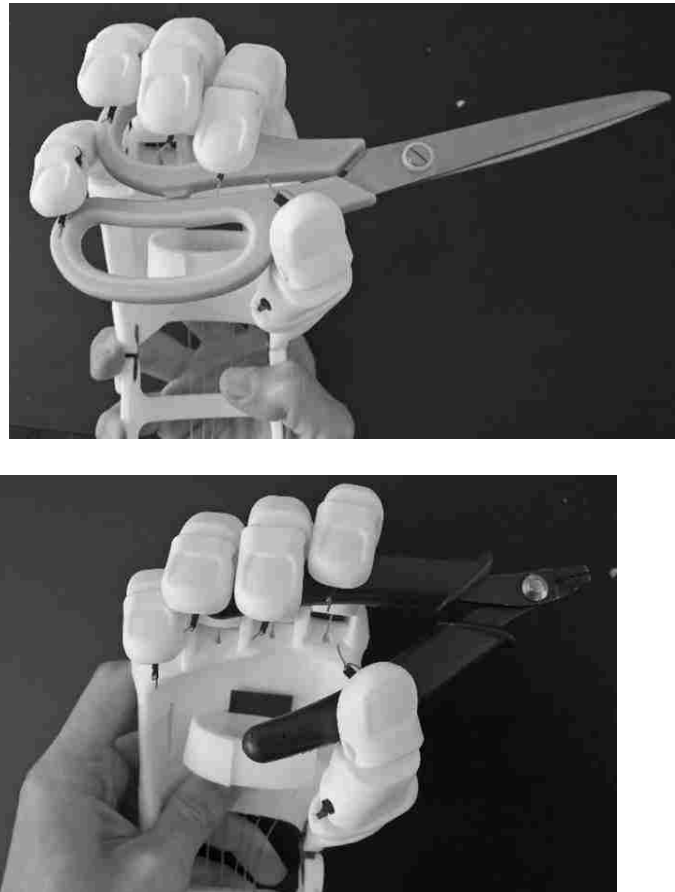


Figure 5.3: Finger Adaptation to Different Shapes

To continue demonstrating the capabilities of an adaptable hand, motion was prevented in the thumb to allow the fingers to move, and vice versa. These two grasps would be impossible in the default hand, as any restriction of motion of one digit prevents the motion of the others. They should allow for greater versatility in grasping more varied shapes in application.

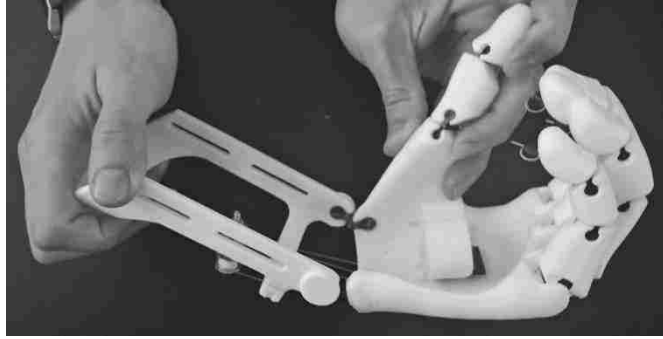


Figure 5.4: Adaptive Grasp with Restricted Thumb Motion

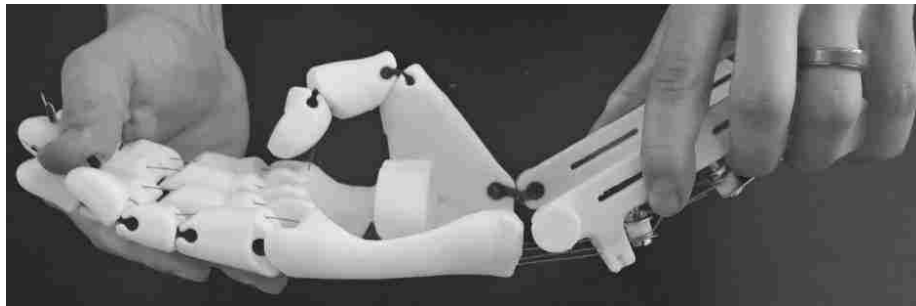


Figure 5.5: Adaptive Grasp with Restricted Finger Motion

Upon failure of the smaller plastic adaptable component, the larger hand-constructed adaptation part was then attached to the gauntlet. This proved more robust than the original system, and equally adaptable.

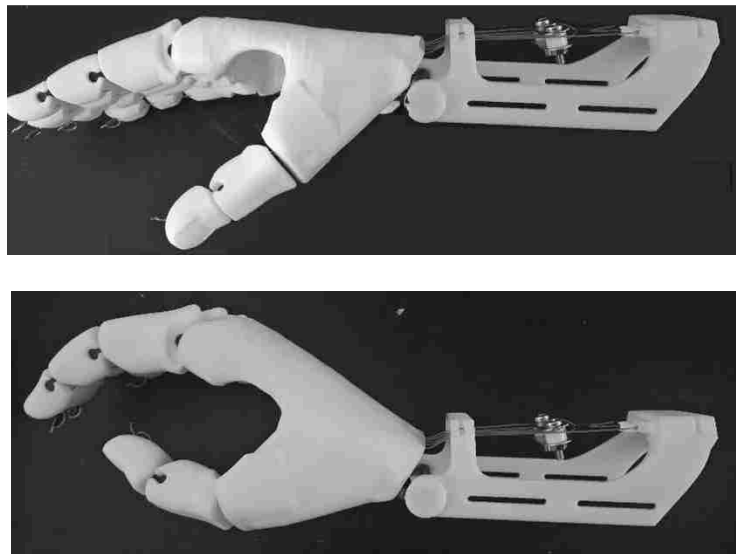


Figure 5.6: Adaptable (above) and Hybrid Adaptable (below) Configurations Used in Testing

The updated configuration was tested normally, and then again with the hybrid setup. In both cases, the adaptive hands out performed the default hands in grip force measurements on the dynamometer, as well as with almost every shape in the weight tests. Similar to the default tests, the higher performance was seen on the tests involving a uniform thickness bar, however the losses in the non-uniform bar seem to be lessened due to possible shape adaptation. The six different test cases (A-F) are summarized in Table 5.3. The maximum grip force and force measurements from each test case are presented in Table 5.4,

Table 5.3: Test Cases

Test A	Max weight with narrow bar
Test B	Max weight with wide bar
Test C	Max weight with sphere shaped bar
Test D	Max weight with variable width bar (wide side near thumb)
Test E	Max weight with variable width bar (narrow side near thumb)
Test F	Max weight with square profile bar

Table 5.4: Setup One Adaptable Hand Configuration Results - Maximum Force in Each Test

Configuration	Grip Force	Test A	Test B	Test C	Test D	Test E	Test F
Adaptable (lb.)	3	8	8	7	7	6	7
Adaptable (kg)	1.36	3.63	3.63	3.18	3.18	2.72	3.18
Hybrid Adaptable (lb.)	4.2	14	12	10	11	10	10
Hybrid Adaptable (kg)	1.91	6.35	5.44	4.54	4.99	4.54	4.54

*Grip force error: +/- 1.13 lbs. or +/- 0.51 kg

5.4 SETUP TWO: DEFAULT AND HYBRID DEFAULT CONFIGURATIONS

The second test setup demonstrated almost an immediate improvement in the default hand, and similar results in the hybrid default. It is important to note that in aside from differences in physical constraints, test results are also influenced by the way it is assembled. Small differences in initial line tension during assembly could change how the hand performs, and a lower tension may yield a lower maximum weight than expected, and the opposite is true for a higher tension. Further iterations of both test setups could be used to better highlight the influence of line tension, physical constraints, and be used to isolate them from the influence of individual configurations.

That said, with the hand suspended and more power available to apply to the hand, results increased for the dynamometer readings at least, and results were similar if not generally improved during testing. The six different test cases (A-F) are summarized in Table 5.5. The maximum grip force and force measurements from each test case are presented in Table 5.6,

Table 5.5: Test Cases

Test A	Max weight with narrow bar
Test B	Max weight with wide bar
Test C	Max weight with sphere shaped bar
Test D	Max weight with variable width bar (wide side near thumb)
Test E	Max weight with variable width bar (narrow side near thumb)
Test F	Max weight with square profile bar

Table 5.6: Setup Two Default Hand Configuration Results - Maximum Force in Each Test

Configuration	Grip Force*	Test A	Test B	Test C	Test D	Test E	Test F
Default (lb.)	4.4	10	10	8	7	9	10
Default (kg)	2	4.54	4.54	3.63	3.18	4.08	4.54
Hybrid Default (lb.)	4.8	12	11	9	10	10	11
Hybrid Default (kg)	2.18	5.44	4.99	4.08	4.54	4.54	4.99

*Grip force error: +/- 1.13 lbs. or +/- 0.51 kg

5.5 SETUP TWO: ADAPTABLE AND HYBRID ADAPTABLE CONFIGURATIONS

When both variants of the adaptable configuration were tested with the crimp rig, both setups were able to achieve higher grip force values on the dynamometer. Although the regular adaptable configuration showed improvement pretty much on every bar, the hybrid adaptable hand was shown to produce very similar results to the testing involving the tester's hand. The six different test cases (A-F) are summarized in Table 5.7. The maximum grip force and force measurements from each test case are presented in Table 5.8.

Table 5.7: Test Cases

Test A	Max weight with narrow bar
Test B	Max weight with wide bar
Test C	Max weight with sphere shaped bar
Test D	Max weight with variable width bar (wide side near thumb)
Test E	Max weight with variable width bar (narrow side near thumb)
Test F	Max weight with square profile bar

Table 5.8: Setup Two Adaptable Hand Configuration Results - Maximum Force in Each Test

Configuration	Grip Force	Test A	Test B	Test C	Test D	Test E	Test F
Adaptable (lb.)	3.8	9	9	7	8	7	9
Adaptable (kg)	1.72	4.08	4.08	3.18	3.63	3.18	4.08
Hybrid Adaptable (lb.)	3.8	9	9	7	8	7	9
Hybrid Adaptable (kg)	2.36	5.9	5.9	4.08	4.54	4.54	4.99

*Grip force error: +/- 1.13 lbs. or +/- 0.51 kg

5.6 COMPILED DATA

Both test setups produced similar trends, it was deemed beneficial to compile each test individually, and then place them side by side for comparison, see Figures 5.5-5.6.

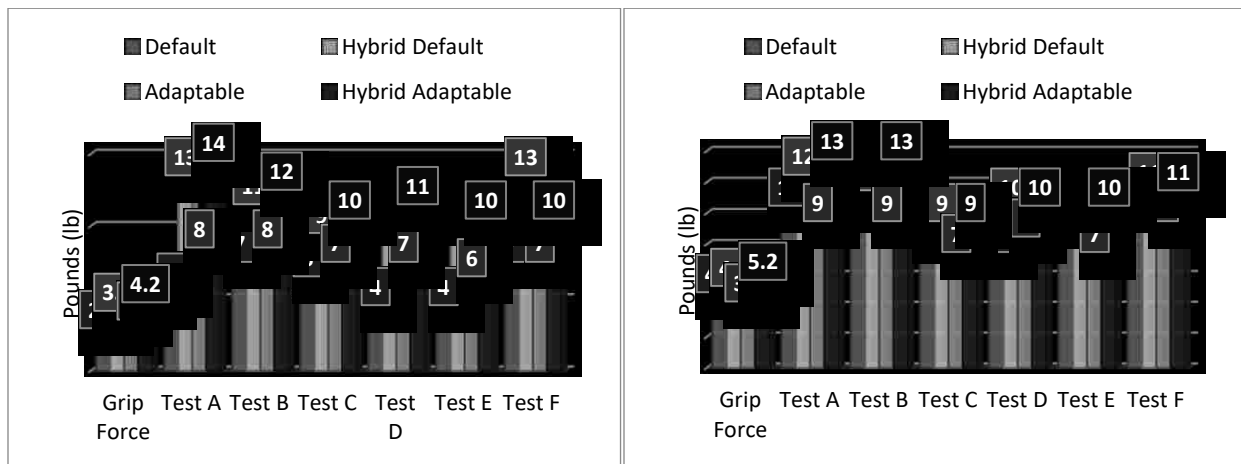


Figure 5.7: Results from Test Setup One (Left) and Test Setup Two (Right) in Pounds

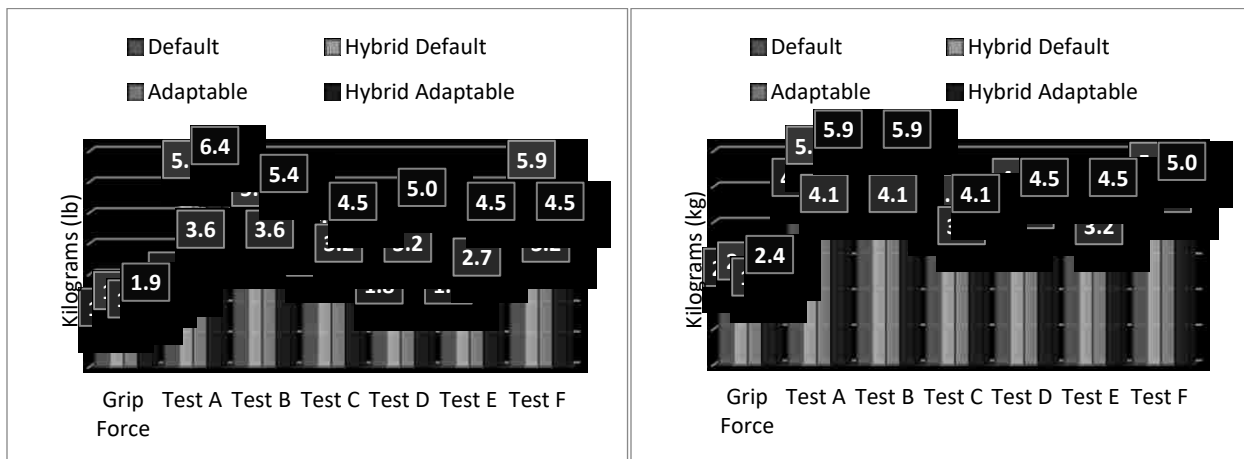


Figure 5.8: Results from Test Setup One (Left) and Test Setup Two (Right) in Kilograms

Table 5.9: Test Cases

Test A	Max weight with narrow bar
Test B	Max weight with wide bar
Test C	Max weight with sphere shaped bar
Test D	Max weight with variable width bar (wide side near thumb)
Test E	Max weight with variable width bar (narrow side near thumb)
Test F	Max weight with square profile bar

What stood out the most was the drastic improvement seen between the results for the default hand in test setup one and two. This may be due to a combination of factors, with the most likely contributors being a potential increase in tension the second time the hand was assembled, as well as the elimination of physical limitations caused by strapping the hand to the tester’s arm. For the other areas, it seemed that performance was very similar.

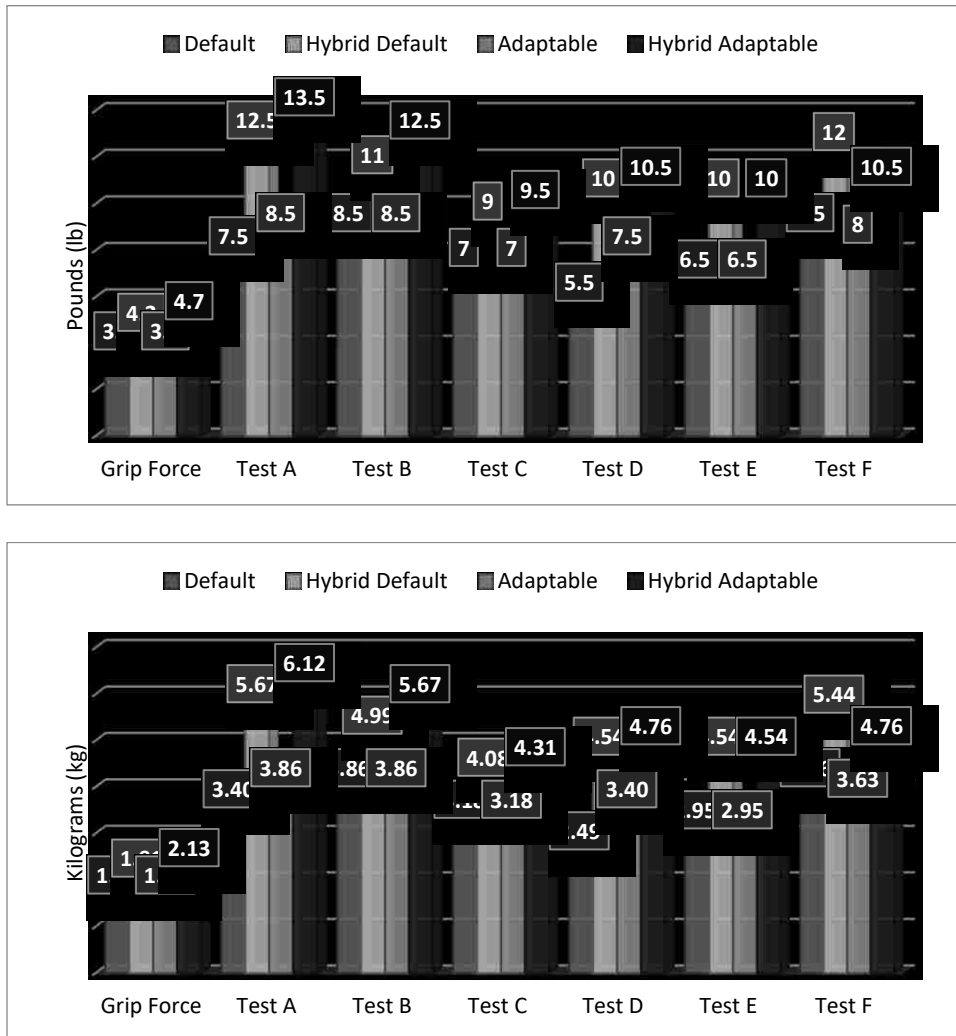


Figure 5.9: Mean of Results from Test Setup One and Two in Pounds and Kilograms

Table 5.10: Test Cases

Test A	Max weight with narrow bar
Test B	Max weight with wide bar
Test C	Max weight with sphere shaped bar
Test D	Max weight with variable width bar (wide side near thumb)
Test E	Max weight with variable width bar (narrow side near thumb)
Test F	Max weight with square profile bar

After the two sets of results were averaged, it became even more clear that the most significant improvement was the addition of a hybrid state to either configuration. With every single test, this simple difference in assembly method added multiple pounds and at least singular kilograms to the hand’s capacity. This benefit is likely due to the effect the tensioning has on the grip behavior; by adding initial tension to the lines, the same degree of added force results in a larger degree of hand closure. This leads to better encirclement of the object, and therefore more contact and friction when are used to securely grasp and object.

The addition of adaptability produced a net positive result, though not so drastic a one as the addition of the hybrid state. In all cases except two (both occurring on test F), the adaptable component equaled or increased the capacity of the non-adaptable hand (this includes comparisons between default and adaptable configurations, and hybrid default and hybrid adaptable configurations.)

With both impacts considered together, it can be correctly deducted that the addition of both a hybrid state as well as the adaptable component equaled or surpassed the next highest result in all tests except one.

To be able to quantify exactly how much of an impact each modification made independently as well as combined, the performance was converted to represent percent improvement of each configuration as compared to the original and is contained within table 5.

The first row represents the difference between default and default hybrid, the second row represents that difference between default and adaptable, and the third row represents the difference between the default and hybrid adaptable configuration.

Table 5.11. Percent Improvement of Each Configuration

Modification	Grip Force	Test A	Test B	Test C	Test D	Test E	Test F	Average
Hybrid	23.5%	66.7%	29.4%	28.6%	81.8%	53.8%	41.2%	46.4%
Adaptable	0%	13.3%	0%	0%	36.4%	0%	-5.9%	6.3%
Both	38.2%	80%	47.1%	35.7%	90.9%	53.8%	23.5%	52.8%

Table 5.12: Test Cases

Test A	Max weight with narrow bar
Test B	Max weight with wide bar
Test C	Max weight with sphere shaped bar
Test D	Max weight with variable width bar (wide side near thumb)
Test E	Max weight with variable width bar (narrow side near thumb)
Test F	Max weight with square profile bar

The above table demonstrates that each modification improves or matches the default hand's performance in all cases except one, and the combination of both modifications is best in almost every case. The average improvement was 46.4 percent for the hybrid modification, 6.3 percent for the adaptable modification, and 52.8 percent for both modifications combined.

6. DISCUSSION

6.1 TESTING AND TEST SETUPS

Throughout the experiments, the main emphasis was on the influence of various factors on the hand's ability to maintain grasp on heavy objects. During these trials, it seemed apparent that the most important factors to achieving and maintaining successful contact with an object are sufficient tension in the lines, and sufficient area of contact with the object. Line tension is important, as it determines both the strength of the grip as well as the amount of object encirclement. When additional tension was added to the lines, it was easier to maintain grasp, as the same amount of wrist flexion resulted in more curvature of the fingers and therefore a more stable resting place to support the weight. This also ties into the second part, the importance of contact area, and therefore friction, between the hand and the object. These factors stood out even more as lifted weight increased and the hand would start to open and extend. In such cases, the weight would be retained by finger curvature alone, and the thumb would no longer be present to help encircle and retain the object.

The use of two different test setups did not demonstrate a significant difference in results, which is actually a good sign. A concern while conducting the first round of testing, was that the hand would be able to support a higher weight than would be physically possible for the tester's muscles to sustain. In addition, the prosthetic is not designed for alternate usage, and the process could not be described as overly comfortable for the tester. If desired, further testing could be done to narrow down the specific influence added by using test setup two, however it appears that useful data could be also be acquired by excluding test setup one from future experimentation. If multiple variants of test setup two were run side by side, even more observations could be made in terms of grip behavior and longevity.

6.2 HYBRID CONFIGURATION

What distinguished the default and default hybrid setups from the adaptable configurations, was both an area of strength and weakness. In a normal setup, each line is independent of the rest, which means that there is no transfer of tension between the fingers. The area this stands out the most is with the thumb, which curls faster than the other fingers. In some cases, this aided with a grasp by causing the thumb to remain fixed near the object and prevent the object from sliding off the fingers. A potential downside however, is if too much tension is added to the thumb's line, it will reach max curvature too quickly and prevent further motion in the rest of the fingers, as all move and stop together. Another problem with independent fingers is the lack of adaptation, where in some instances only the thumb and first two fingers were in contact with the object.



Figure 6.1: Problematic Grip Patterns with Independently Strung Fingers

Without clinical testing, it is difficult to know whether the initial finger curvature present in the hand would be a limiting factor when encountering large objects, or whether lifting the wrist in the opposite direction would lead to a wider opening. Further testing should be conducted with hybrid setups and light objects of varied shapes to determine the variation's effectiveness in a wide variety of object interactions.

6.3 GRIP FORCE CONFIGURATION

Although it proved too difficult to demonstrate, the idea behind a grip force magnifying configuration still warrants investigation. The hope behind it was that such a modification would allow the fingers to be more responsive to wrist motion, resulting in a tighter grip, and a wider open state. This would have been accomplished by adding a line which would cause the other lines to tighten when the hand was flexed. Instead of accomplishing this, it seems likely that instead of freely adding tension to the fingers, the line became fixed where it was. When force was added to the wrist, instead of causing the fingers to curl even more, the line that added tension either seized or failed. In fact, the only time such a hand resulted in a measurement of force, the value was identical to the default hand without any sort of force magnification. This indicated that something was not working as intended. If this idea were to be implemented again, a potential fix would be to add an actual moving pulley and hopefully prevent the line from seizing.

A demonstration of where a similar concept worked, was with the adaptable configuration. When the thumb motion was restrained, the remaining tension was transferred to the fingers, causing them to flex. The original setup was supposed to do the same for the thumb as well as the fingers all at the same time.

6.4 ADAPTABLE CONFIGURATION

The adaptable configuration proved exceptional at accommodating different object shapes. When the object weight was on the lower end, the thumb and all fingers would tighten until each was firmly grasped around the object. This customized resting place was very secure and resulted in a high degree of contact and friction when it could be properly maintained.

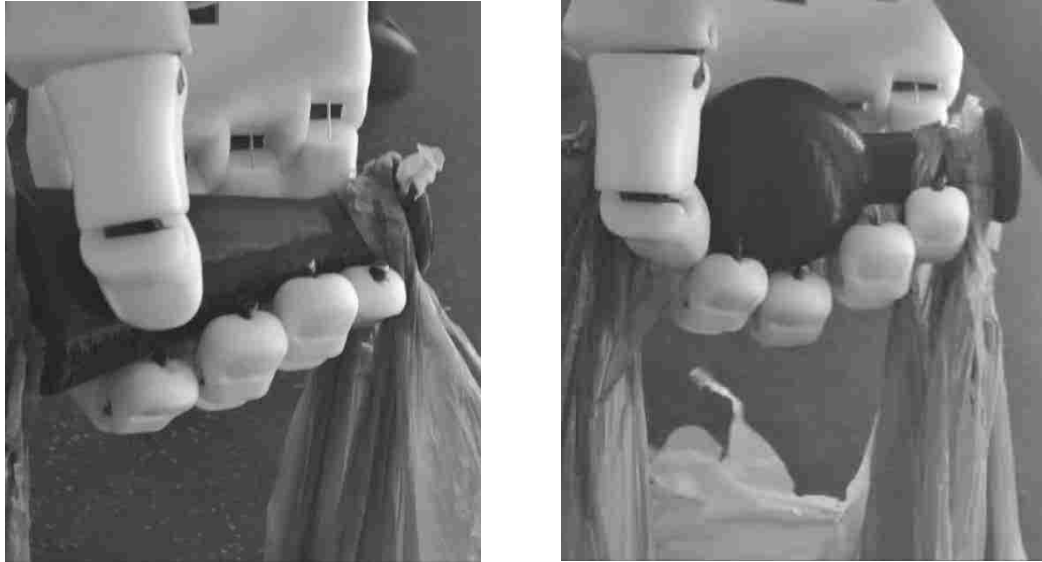


Figure 6.2: Grasp Adaptation to Various Bar Shapes

In higher weight scenarios however, the object would be pulled out of the thumb and tension would be expended in continuing to tighten the now-unrestrained digit and it would not be able to act as a barrier against motion.



Figure 6.3: Adaptive Hand Response to Higher Weight Loads

This may indicate that adaptation may prove more beneficial achieving sufficient friction with lighter objects, and that grasp approaches that facilitate continued thumb contact may allow for even heavier weights than tested to be sustained.

6.5 COMPARISON TO NORMAL APPLICATION

It is important to note that although the data is potentially useful in evaluating differences between different hand configurations, there are some important distinctions between the testing scenarios and real life.

First and foremost, different physiology was utilized to power the hand's grasp in both test setups. Considering that the palm area was meant to accommodate individuals who are missing most or all of their digits, there was not room in the first setup to attach a five-fingered hand. As such, instead of attaching around the palm, and powering the hand with the wrist joint and musculature, three fingers were used as an attachment point, and a combination of finger, palm and some wrist muscles were utilized instead. The testing proved difficult, and had the hands performed even better, it is possible that tester strength could have become a limiting factor. In the second test setup, force was applied externally and involved larger muscle groups (bicep/shoulder etc.) than would normally be involved with prosthetic use.

Secondly, the experimental tasks were intended to evaluate maximum grip strength and do not represent the wide variety of potential interactions faced in real life. There is no question that the improvements could make a difference in prosthetic performance, but that is something that will have to be tested separately. One thing that this data has in its favor, however, is that day-to-day interactions are full of various "bar" shapes, from handles on luggage, doors, and drawers, to latches, handlebars on bikes, rails, and many more, and the ability to apply or resist a higher force is surely desirable.

7. CONCLUSIONS

Research has determined that not only are prosthetic wearers dissatisfied with their devices, but that performance has not changed significantly in decades. The problem seems to lie not with a lack of research, but rather with the repeated trend of ideas resulting in hands being built from scratch and failing to out-perform their current counterparts. The purpose of this work was to demonstrate that testing and innovation could be sped up by taking advantage of 3D printing, and that research could be made more scientific through the introduction of modularity. The modular 3D printed platform was then utilized to demonstrate the impact small improvements could have on the hand's performance.

To demonstrate the impact 3D printing could have on the process of prosthetic development, a device design was located on the internet, modified, and produced. Various components were also printed or purchased which would allow the device's performance to be manipulated and tested. Although some of the parts experienced strain and failure, these challenges proved easy to overcome, and the entire process was completed in a timely and cost-effective manner. This means that if another location with a printer were to receive the files and data, that these experiments could be repeated or even improved upon remotely. Alternatively, certain concepts could be taken from this experiment to be applied to a completely different basic hand design, and an even more complex set of experiments could be run.

Modularity was implemented on the chosen hand through the development of different ways the finger lines could be configured, to test different principles. Overall, these configurations only required the fingers to be restrung in different ways, which was quite straightforward. It is also conceivable that a researcher could print out more hand copies, and configure each one separately and could eliminate the need for reassembly between tests. This research avoided the

pitfalls of prior testing, which almost always has involved comparing performance of hands with differences that could include shape, material, joint mechanisms, presence of springs or elastics, the use of a cosmetic cover, the additive mechanisms to implement a specific function among others. Instead, this work demonstrated that a single platform could be easily modified to respond in different ways, and that the performance could be compared with almost all other variables remaining the same.

The various configurations were intended to prove the efficacy of improving grip force and responsiveness, grasp adaptation, and variable direction of closure. Each setup uniquely impacted the devices performance, and each could be modified and implemented in future testing.

The modification to magnify grip force was not proven to be effectual, though the theory still seems sound. A line was intended to cause the hand to tighten further when the hand was moved, however, it did not transfer tension to the fingers as intended, and instead made it difficult to close the hand. The likely culprit was the static pulley parts that were utilized to allow the lines to move, but instead the lines caught and acted as if they were attached at the point where they were supposed to slide. It is possible that if the static pulley were replaced with a moving pulley, that the mechanism might work as intended. This could allow changes to be made that affect how responsive the fingers are to wrist motion, either by making them more responsive and requiring more strength from the wearer, or slightly less responsive and requiring less from the wearer.

Although the original mechanism of adaptation failed in testing, it proved to allow adaptation, and a hand-made replacement proved durable and effective enough for testing. A combination of sliders and pivots allowed for the hand to adapt when encountering abnormal shapes. In the non-adaptive setup, when a finger's motion is obstructed either by reaching maximum curvature or by encountering an immobile shape, the rest of the fingers also stop

moving. The adaptive configuration allowed for tension to transfer between digits, so other fingers could continue to tighten around a shape even after one digit was constrained. This is beneficial to real life, as it could allow the hand to accommodate to a wider variety of shapes, and grasp more successfully by increasing surface area of contact, and therefore friction.

The change that had the largest impact on testing was a modification to change direction of motion. With this modification, the hand was pre-tensioned so that at rest, the fingers retained some curvature. This was intended to utilize a lifted or extended posture of the hand to grasp objects, and to yield greater net finger curvature with wrist flexion. The greater degree of curvature proved beneficial to testing, as the fingers could retain differently shaped bars with higher weights attached to them. It remains to be seen whether this partial closure also makes it more difficult to open and accommodate larger objects, and further testing is required to determine optimal pre-tensioning if the concept applies well to real life.

8. FUTURE WORK

Undoubtedly, the most efficacious follow-up to this work would be for these modifications to be setup and tested by individuals who would normally wear such a device. Input from clinical trials and comparisons, as well as observations from practical use could help shape modifications to design as well as the development of novel testing parameters. If rounds of future modifications were interspersed with rounds of clinical verification, various innovations (potentially beyond what was tested here) could rapidly be evaluated for continual improvement or elimination. In lieu of clinical testing, a repetition of similar experimentation with a more drastic shape variation could better emphasize difference caused by mechanisms such as the one which added adaptation. In addition, testing could be done to see what hand configurations are able to grasp un-weighted real-world objects of varying shapes, to better simulate day-to-day object interaction.

Another area of potential consideration would be the addition of markings to the hand and gauntlet in order to evaluate the wrist angle required to sustain each grasp. If the hybrid setup were to be tested in the future, it may be worthwhile evaluating what initial angle of curvature exists due to pre-tensioning. If testing were to be run as in this study, final angle (or change in angular position) could be recorded for each grasp and used to evaluate the experience of the wearer. Alternatively, a specific final angle could be chosen, and maximal weight load per that wrist angle position could be determined with that limitation in place.

Another modification that is worth developing is the addition of another joint between the palm and the thumb. Quite a few of the inspected designs implemented a mobile thumb, and it could help performance and grasp efficiency. Part of the reason why the thumb is so complicated, is that in normal use, the thumb shifts through a wide variety of angles and positions, so a thumb with one position (even if mobile) is quite limiting. Another reason why the thumb should be

investigated is that it is the fastest closing digit. In the default setups, having an over-tensioned thumb could limit the degree of closure that the other fingers are capable of, so the addition of another joint would mean that the thumb responds more similarly to the other fingers.

One small change which could make a difference in performance is the addition of friction pads on the fingertips as well as on the insides of the individual phalanxes. This could help to add to grasp efficiency by increasing the static friction between the hand and the object grasped.

Lastly, this work could be used for the purpose of adapting modularity and individual improvements to other hand designs, as well as to other prosthetics that may utilize a different joint for power. The concepts tested here could prove beneficial to both BP and EP prosthetics, especially if a cable is utilized at some point in the design.

All design files used in this research can be found online for further study or experiment recreation [54].

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University of Nevada – Las Vegas: Las Vegas, NV

- Redesigned, 3D printed, and assembled various iterations of an open-source CAD prosthetic hand for a child whose fingers did not develop completely on her right hand

Graduate Assistant/Class Instructor September 2014 to December 2016

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- Led an introductory robotics lab which emphasized innovative problem solving and culminated in a competition between students
- Instructed a 3D modeling Solidworks course by demonstrating essential skills and creating novel assignments and activities

Accident Reconstruction Specialist June 2015 to December 2015

American Bio Engineers – Las Vegas: Las Vegas, NV

- Performed biomechanical analysis on auto accidents of varying severity using photogrammetry, simulation software, and laser scanning in order to estimate relevant forces and velocities

Advanced Neuroscience: Teacher's Assistant and Research Team Lead January to December 2013

Brigham Young University – Idaho: Rexburg, ID

- Helped institute and design a new research project to investigate crayfish neurogenesis
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Research Assistant and Engineering Intern, R&D September 2011 to April 2012

Second Sight Medical Products Inc.: Sylmar, CA

- Utilized existing resources to design, modify and perform a novel research experiment
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PUBLICATIONS

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Third Place at Research & Creative Works Conference (Poster Presentation) April 2013
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Annual BCI Research Award Nominee October 2012
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