# The Yale MyoAdapt Hand: A Highly Functional and Adaptive Single Actuator Prosthesis

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Abstract—The drawbacks of many commercially available multi-actuator prosthetic hands have led to high rejection rates in both adults and children. For an active lifestyle, there is a need for a device that is both lightweight and easy to control. Underactuation has quickly become an attractive solution in prosthetics by reducing the control burden and the weight of multi-actuator hands while still providing a compliant anthropomorphic grasp. In this paper we present the design and evaluation of a novel single actuator prosthetic hand. The hand uses adaptive mechanisms to allow for three unique grasp types with varying grasp rates, force output and thumb positions. The hand kinematics and geometry are optimized to prevent against common grasp failure modes of underactuated grippers. The hand was evaluated through benchtop and human subject testing to evaluate its effectiveness on activities of daily living. Additionally, we compared the performance of the hand to previously published results from a powered hook, a single actuator anthropomorphic robotic hand, and several commercial multi-actuator anthropomorphic robotic hands. The results show that the hand is comparable even to multiactuator commercial devices with users who have trained on these devices for several months to years.

*Index Terms*—Prosthetics, Rehabilitation Robotics, Grasping, Robot Kinematics, Benchmark Testing.

## I. INTRODUCTION

There are currently over five hundred thousand upper limb amputees in the United States - expected to double by the year 2050 - consisting of 61% with transcarpal amputation, 15% with transhumeral amputation and 12% with transradial amputation [1]. The last century has seen significant improvement in upper limb prosthesis design, moving from either passive cosmetic devices or simple body-powered designs to more functional human-like hands. This change has been driven by more effective rehabilitation techniques and amputees moving from more passive to active lifestyles [1]. Functional myoelectric prosthesis can be separated into two primary categories: electrically actuated task-specific devices and electrically actuated anthropomorphic hands. Task specific devices, such as parallel jaw grippers [2] or split hooks [3], are preferred for their control simplicity, light weight and grasp speed. This allows these devices to form a quick intuitive grasp with simple, sometimes even single sEMG site, control. In contrast, more complex multi-actuator anthropomorphic hands [4][5], are preferred for their anthropomorphic appearance, multiple distinct grasp types, and high grasp force. This allows the user to operate a terminal device that looks and functions like a human hand. However, these multi-actuator devices



Figure 1. The Yale MyoAdapt Hand displaying interfinger passive adaptability from the coalesced whiffletree differential mechanism.

usually require extensive training times to master and can be excessively heavy and costly.

Even with recent advancements, there is still no defined solution to upper limb amputation because every amputee has difference preferences and requirements based on age and lifestyle. Including the recent advancements in prosthetics rejection rates remain high including up to 23% adult device rejection and 35% pediatric device rejection. This has been partly attributed to lengthened training, high power consumption, reliability on multiple electrodes, lack of grasp adaptability, grasp speed, durability, weight and cost [6]. Lengthened training poses an issue because it is discouraging to slowly progress at operating a more complex device which is nominally seen in multi-actuator devices with more complex control. Next, using multiple actuators help provide more grasp force but requires more power to operate. This then requires the amputee to charge the hand more often which can be minimal if a full charge can last a majority time the amputee requires the hand. Next, electrically actuated hands tend to have significantly slower closing rates than the 300 degrees/second finger angular joint velocity seen in the human hand [7]. This is a result of high gearing on electrical actuators to increases grasp force. Other issues with electrically actuated anthropomorphic hands include durability especially at the finger joints, excessive weigh which causes fatigue when worn for prolonged periods and cost, especially for hands with multiple actuators.

Alongside the physical capabilities of the actuators, control can interfere with the hands ability to perform. The need to rely on multiple electrodes simultaneously for complex anthropomorphic devices may pose issues while controlling the device or may not be operable by amputees with limited access to EMG locations or signals. An advantage of more simple task specific hands is intuitive simple control, however, these hands usually a lack of grasp adaptability or lack of grasp types to accompany a variety of objects that the more complex hands can. This makes simple control architectures for simple devices very good at grasping certain objects, such as a flat object for a parallel jaw gripper, but less successful on grasping objects that are vastly dissimilar to local geometry, or may have been designed to be ergonomically grasped by hand-like architectures.

These practical limitations have led to electrically actuated designs that aim to fuse the functionality of simple single actuator task-specific devices and multiple actuator anthropomorphic hands through the implementation of underactuated or differential mechanisms [8][9]. Whereas most electrically actuated prosthetic hands have a single motor for each finger, underactuated hands have fewer actuators than degrees of freedom. Underactuated mechanisms allow for less demanding control by passively transferring motor torque to multiple fingers. This provides a purely mechanical means for grasp adaptability and distribution of actuator torque across larger contact areas. This "mechanical intelligence" is inherent in the mechanisms structure and requires no additional control to create an adaptable secure grasp.

These underactuated devices rely on differential mechanisms to couple the joints and/or fingers, such as pulley transmissions [10], Geneva mechanisms [11], moveable pulleys, various geared differentials, and whiffletree mechanisms [12][13]. The fingers themselves are usually underactuated, either through linkage structure that couples joint motion or through the use of elastic flexures or springs connected through a transmission ratio. A significant number of these hands use two to three dc motors, typically actuating the forefinger and thumb flexion as well as the thumb position [14][15]. Some hands that we consider "highly" underactuated have one actuator driving nominally 15 degrees of freedom in an anthropomorphic prosthetic hand [16-18]. These hands sometimes allow the thumb to be passively rotated to accompany a variety of different object sizes, however, lack distinct grasp types with varying force production and closing rates of more complex anthropomorphic hands [4][5]. Underactuated hands are a middle ground of task specific and more complex anthropomorphic hands by providing force balancing and grasp adaptability with simple control in a lightweight and low-cost package.

In this paper, we propose the final version of an initial prototype [19] single actuator anthropomorphic prosthetic hand. We focused this hands design on addressing the tradeoffs of more simplistic task specific hands with that of more complex anthropomorphic hands by providing multiple distinct grasp types from a single actuator. This was accomplished by using underactuated mechanisms in both the transmission and finger design to allow for multiple passively adaptive grasps. After the design was finalized, the hand was optimized to provide kinematics, grasp topologies and finger pad surfaces to improve upon the last version and aid precision grasping tasks that remain difficult for many amputees [1].

After development, we evaluated the hand through benchtop testing and a human participant study (IRB HSC #1608018242). In the benchmarking study, we evaluated hand performance through a variety of metrics such as grasp force, aperture and speed. This was to ensure the hands performance aligns with the specifications necessary for these devices outlined in previous literature. In the human participant study, we evaluated the device with ten able-bodied participants that completed repetitive pick and place, abstract objects and activities of daily living tasks. The hands performance was then compared to the participants able-bodied hand and a variety of studies with other commercially available electrically actuated task-specific and anthropomorphic hands.

## II. UNDERACTUATED MECHANISM DESIGN

The concept of underactuation, where a mechanism has fewer actuators than degrees of freedom, has been leveraged in prosthetic hand designs to decrease control complexity and cost while still providing a compliant multiple finger grasp. Previous research has shown that underactuated hands can adapt to a variety of object sizes and geometry using either open-loop or simple close-looped control [8]. However, these devices are commonly only capable of a single grasp when compared to the multiple grasp types that are made easier in hands with several motors. Our goal was to be able to create a single actuator anthropomorphic hand with the several adaptable grasps seen in more complex multiple actuator hands. This hand, the Yale MyoAdapt hand, is capable of three grasp types including a power grasp, a tripod grasp and a lateral grasp. These three grasp types were chosen based on their higher frequency usage by amputees in everyday activities [20]. In this section, we will discuss the underactuated mechanisms implemented in this hand to allow for multiple distinct underactuated grasp types. This includes the hand transmission design, finger coupling and locking mechanisms, thumb positioning and finger design. We will proceed through these mechanisms starting from the internal differential transmission mechanisms and ending on the distal underactuated fingers.

#### A. Hand Transmission Design

The MyoAdapt hand is considered underactuated because it has one degree of actuation (DoA) for its ten degrees of freedom (DoF). This active degree of actuation is from a single brushed DC motor (*Faulhaber 1524SR*) that is diagonally placed in the 50<sup>th</sup> percentile female sized palm chassis due to packaging constraints (fig 2.). We found this orientation was favorable for fitting larger higher torque motors within the palm. The single motor drives five two-jointed fingers totaling to ten degrees of freedom. There is a single manual degree of freedom that allows the thumb to reposition and lock from forefinger opposition to lateral opposition. Last, there is another passive rotational degree of freedom made possible by the flexure spanning each fingers distal interphalangeal joint.

The single actuator is first attached to a planetary gear stage that drives a single worm gear pair. These two initial gear stages provide mechanical advantage through gear reduction (820:1). The worm wheel also provides non-backdrivability to avoid excess power consumption from motor stall while grasping. The worm wheel drives an output shaft which has three main tendon pulley drives attached. The output shaft is keyed at different radii to precisely align the three output pulleys. The anterior palm pulley is slightly smaller and drives the thumb. A larger pulley in the posterior palm drives the forefingers through an underactuated finger coupling mechanism. This pulley is larger because the torque must be split between four fingers creating an asymmetrical rate of closing between the forefingers and thumb. This difference in pulley radius between the thumb and forefingers allows us to provide a more anthropomorphic grasp as well as create unique tripod and power grasp timings through the use of an internal locking mechanism. This locking mechanism is driven by the third output shaft pulley in the middle of the palm and consists of two antagonist tendons that create the transition between power and precision grasp. We will discuss how this transition is automated in the next section.

The grasps are controlled through closed-loop feedback with a simple current sensor to identify when an object has been successfully grasped. If the current limit is not met, each grasp has a calculated excursion that is determined from a high resolution 2-channel magnetic encoder attached to the back of the DC motor. We consider two encoder positions for each grasp, the grasp start ( $L_{Tendon\_Start}$ ) and grasp end ( $L_{Tendon\_End}$ ). These values vary depending on the grasp mode that is currently selected. The power grasp spans the full range of actuator excursion while the precision and lateral grasps both have around half that excursion. This allows for a slower wider aperture power grasp and quick smaller aperture precision and lateral grasps. The varying motor position for each grasp is created through the use of two active locking mechanisms which we will discuss in the next section.

## B. Finger Coupling and Locking Mechanism

The forefingers are driven by a single differential mechanism that is coupled to the output shaft of the gearbox. This modified whiffletree mechanism has been coalesced to fit within the small size of the hand and provides differential motion between each of the three fingers from the single input tendon. All four fingers have a similar pulley radius and spring stiffnesses at the proximal and distal joints. This ensures that under no loading the forefingers have similar excursion and will close at the same rate. The exact kinematic specifications of these transmission ratios and spring stiffness are decided from an optimization study [19] that will be provided in the next section.

The coalesced whiffletree mechanism consists of three bars, one that attaches to the central output shaft tendon, and then two identical bars that attach to the index-middle pair and ringpinky pair. Each tendon routing is countersunk and then epoxied to both protect and fasten the knot at the end. The whiffletree provides an adaptive grasp by allowing the two pairs to move independently of one another while allowing each pair to move independently through rotation of the distal bar. This provides a slight coupling between the fingers in each pair which we found to be beneficial during tripod grasping [19]. On the backplate of the main whiffletree backplate, there is a slot that constrains the distal bars to prevent misalignment of the output tendons. With this mechanism we can provide eight degrees of freedom – two for each finger – from a single tendon off of the output shaft. This includes additional adaptability



Figure 2. (Top) The actuation morphologies for the whiffletree mechanism in power (left) and tripod (right) grasps. (Bottom) In power grasp the whiffletree is free to move actuating all four forefinger outputs. In tripod grasp the whiffletree is locked providing the actuation force through a lever arm to the index and middle fingers. In lateral grasp, all forefinger motion is restricted and only the thumb is driven.



Figure 3. The three stages of the four-bar bistable mechanism that provides passive thumb locking and rotation. The thumb rotator is attached to the red linkage which rotates the thumb between the power and lateral opposition positions. When in the singular bistable orientation, the torsional spring located at the intersection of link  $r_1$  and  $r_4$  drives the finger to lock in either of the power or lateral positions.

while grasping at the distal flexure joints that have the ability to conform to objects out of the finger grasping plane. Our group has investigated using floating pulleys [22] to alleviate all forefinger motion coupling, however, we believe that this makes the hand significantly more difficult to fabricate with limited benefit especially in tripod grasp.

Along with the whiffletree there is a locking mechanism in the backplate that rotates to automatically switch between power and tripod grasp types. In power grasp, the thumb opposes the index-middle pair and each finger closes at a similar rate until an object is acquired or the grasp is completed. In tripod grasp, the ring-pinky pair of the whiffletree is locked closed by this mechanism, creating a new lever arm actuation method with only two degrees of freedom. The new actuation lever arm provides twice the closing rate with a lighter grasp force which is necessary for acquiring smaller or lighter objects. Additional slack is removed so that the grasp starts immediately when the grasping signal is passed. Locking and unlocking is automated through a rotating slotted cylinder that is driven by two antagonist tendons on the output shaft. When the output shaft closes the hand in power grasp, an additional quarter turn of the output shaft will drive the switching tendon, locking the ring-pinky member in place. Because this is a tendon, the ringpinky will remain locked until it is released. The transition back to power grasp occurs when the hand is completely open in tripod grasp and the motor is run backwards past the initial datum. This drives a tendon resetting the slotted cylinder and releases the ring-pinky member to open the hand into power grasp.

#### C. Thumb Positioning Mechanism

The hands third grasp is a lateral grasp, where the thumb is in opposition with the proximal link of the index finger. This grasp is selected through a manual rotation of the thumb when the hand is already in tripod grasp. This motion displaces a tendon connected to the index-middle whiffletree member with the thumb abductor locking the two fingers closed. In lateral grasp, the thumb aperture is reduced and actuator force is allocated to the thumb driving tendon. This allows for a strong small aperature grasp necessary for lateral grasp activities of daily living, including turning a key or holding a mug.

In a previous version [19], the tripod-to-lateral transition was also manual. The user had to press and hold a button to unlock and lock the finger into the power/tripod and lateral grasp locations. We found this was too complicated of a transition for bilateral amputees, requiring the amputee to both press and hold the selector button and then manually rotate the thumb. We found that a four-bar bistable mechanism is a simple and robust solution that can simplify this motion by eliminating the need for a selector button but still provide the required locking.

This four bar mechanism (Fig 3.) provides force through a spring that locks the thumb in the correct anatomical positions for power, tripod and lateral grasps. When designing a planar four bar linkage, there are many things to consider that will alter the coupler curve of the mechanism. First, we considered a planar quadrilateral linkage with four revolute joints (RRRR). Due to the sizing constraints, we required the thumb rotational axis to be small, making a crank-rocker architype ideal. To determine whether or not a planar four-bar linkage will act as a crank rocker, we must first take into account the Grashof Condition to determine if our input thumb motion (crank) will be constrained during the transition.

$$S+L \leq P+Q$$

Where S and L are the shortest and longest links in the mechanism and P and Q are the two middle length links. Once this is satisfied, we have ensured that the crank will be able to fully rotate in the required anthropomorphic range. We can then determine if the relative coupler motion using the below equations corresponding to Fig. 3 [23].

$$T_1 = r_1 + r_3 - r_2 - r_4$$
  

$$T_2 = r_1 + r_4 - r_2 - r_3$$
  

$$T_3 = r_3 + r_4 - r_1 - r_2$$

Where  $r_2$  is the input link length,  $r_4$  is the output link length,  $r_1$  is the ground length and  $r_4$  is the floating link length. When all three of these criteria are positive, we can assume our input thumb motion will operate as a crank with a full range of rotation and our output linkage coupler curve will operate as a rocker. The crank-rocker relationship was chosen over a crank crank relationship because we would like this mechanism to be bistable. Bistability in a crank rocker system will allow us to use a single spring to apply force to lock the thumb in either position by manually sliding the thumb through the mechanisms singularity point. Bistability in crank-rocker systems with a single spring is ensured when the following equation is satisfied [23].

$$K_4(\theta_4 - \theta_{4i})\frac{d\theta_4}{d\theta_2} = 0$$

Where  $K_4$  is the output linkage spring stiffness,  $\theta_4$  and  $\theta_{4i}$ are the final and initial angle of the output link, and  $\theta_2$  is the angle of the input link. When this relationship is satisfied, we can solve the systems kinematics to select the starting angles and link lengths that make sense for our given packaging constraints. We solved this using a nonlinear optimization (MATLAB) framework given that we wanted the input crank to have  $(\theta_2 - \theta_{2i}) = 90^\circ$ ,  $r_2 = 0.5$  inches and the point of bistability to be when  $\theta_2 = 45^\circ$ . With these constraints ensured,



Figure 4. The basic robotic linkages are evaluating kinematic parameters seen in a human precision grasp including all angles, link lengths, stiffnesses and transmission ratios for the thumb, forefinger and palm. This asymmetric precision grasping optimization investigated (a) the stable contact of a range of object sizes for a given precision grasp, (b) the minimization of post-contact work for the fingers and object and (c) the configurations resistance to external wrenches after the object has been acquired.

the spring applies a locking force into both thumb orientations selected through the singular orientation. We then selected a torsional spring stiffness (0.02 Nm at max) that was as rigid as possible to ensure the thumb would remain against each hard stop but still allow the amputee to feasibly rotate the thumb through the singularity point.

# D. Finger and Palm Chassis Design

The palm and finger components are anthropomorphically sized to a 50<sup>th</sup> percentile female hand [24]. This includes accurate joint positions for the forefingers and thumb in relative elevation, positioning and abduction angle. Slight differences include a slightly larger protrusion by the thumb MCP for the thumb rotator and a slightly larger proximal link for the index finger to better align the hands tripod grasp. Each finger consists of two links, one proximal and one distal, that begin at the metacarpophalangeal joint (MCP) and the proximal interphalangeal joint (PIP). The proximal link is the measured distance from the MCP to PIP and the distal link is the measured distance from the PIP to the distal fingertip with a slight bend (approx. 20°) at the distal interphalangeal joint (DIP). This slight bend is to improve alignment for the tripod grasp while also providing an additional point of contact during power grasp. At the base of the palm there is a standard 1/2"-20 threaded post for socket integration with two rubber o-rings that help passively set the wrist position.

The palm and finger chassis are made of ABS plastic reinforced with 40% fiberglass by volume. This allowed for a slightly stronger and heavier chassis than our initial prototype. However, 3D printed plastic does not have the strength required for everyday use, especially in a commercial product. We have investigated other ways to manufacture stronger and lighter prosthetics using composites [25] that may be more suitable for daily use. Both the palm and finger pads have urethane gripping surfaces (Smooth-On, Vytaflex 40) to help promote more contact during precision and power grasping. The proximal index finger pad has an extended grip pad to promote additional contact for lateral grasp. These grip pads were optimized to promote contact for a variety of object sizes and geometry, which we will discuss in the next section.

The fingers consist of several components on top of the 3D printed chassis and urethane gripping surfaces. For all five fingers, MCP joint consists of three main components to allow the finger to passively open after a grasp and to eject under high loads to protect the finger. On a previous version of the hand [19], the MCP joint consisted of two half spring plungers and a torsional spring that created significant friction at the joint, ejected at too low of forces and misaligned the joint torsional spring. In this version of the hand, we improved this design by using an off the shelf quick release spring bar that allows the fingers to be quickly inserted or ejected under unfavorable loads. This spring bar acts as the joints center of rotation and is fixed within a guiding sleeve attached to the finger chassis. This guiding sleeve has a slot that ensures the torsional spring is centered. The distal PIP joint consists of an elastic flexure that provides in-plane bending and passive out-of-plane reconfiguration for the distal link. This flexure has embedded cloth in the neutral axis to mitigate axial stretch and provide additional out of plane stiffness while still promoting a smooth bending motion during finger actuation.

The finger tendons are tensioned to the differential whiffletree mechanism through a tensioning mechanism in the distal fingertip. This tensioning mechanism consists of a canulated screw and hex nut that can adjust the tendon knot position within the finger. This is necessary to pretension the finger to ensure uniform force transmission and closing rates. This tensioning mechanism is hidden under stainless steel fingernails that were designed to snap onto the distal end of the fingers. Just like in the human hand, our rigid fingernails work with the soft finger pad directly below to create a pocket that provides a soft compliant grasp of very thin or small objects. We found that extending the distal grip pad area up to the fingernail was necessary for grabbing very thin objects, as hard contact would lead to object ejection. Excess friction in the system is mitigated with guiding tubes and capstans to stop the tendon from wearing the 3D printed chassis. System drive electronics were mounting externally, however, were included in the mass rollup and are intended to be integrated into the hand in the future.

TABLE I. ASYMMETRIC SIMULATION RESUL	JLTS
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	Stable Reconfiguration (0% to 50% $L_f$ )						
Param.	Min	Mean	Max	Range	Tested	Local	
FF Trans. Ratio $(R_2/R_1)$	0.083	0.233	0.550	[0.083-1]	0.083	0.077	
FF Joint Position $(L_2/L_1)$	0.682	0.831	1.450	[0.68-1.45]	0.682	0.514	
FF Stiff. Ratio $(K_2/K_1)$	1.273	3.585	8.400	[0.01 − ∞]	8.400	9.130	
T Trans. Ratio $(R_4/R_3)$	0.025	0.054	0.066	[0.01-1]	0.055	0.049	
T Joint Position $(L_4/L_3)$	1.098	1.099	1.100	[0.9-1.1]	1.100	1.100	
T Stiff. Ratio $(K_4/K_3)$	10.63	13.35	28.11	[0.01 − ∞]	12.62	14.22	
Initial FF Angle $(\theta_F)$	50.00	50.51	70.00	[50-70]	50	55	
Initial T Angle $(\theta_T)$	10.00	15.83	30.00	[10-30]	20	18	
Palm Width $(L_p)$	1.243	1.456	1.500	[0.5-1.5]	1.456	1.473	

#### III. KINEMATIC AND GEOMETRIC OPTIMIZATION

The transmission design is important to the performance of a hand but does not fully define the critical aspects of the grasp, such as motion envelope or grasp stability. In this section, we will discuss the framework developed to optimize the kinematic properties and finger pad geometry of the hand (Fig. 4).

## A. Kinematic Optimization Study

To establish the optimal kinematic parameters for this hand, we modified a constrained optimization framework we previously developed [21] to evaluate favorable symmetric precision grasping parameters. This framework created was to address the issue in highly underactuated grippers when it comes to post contact stability in precision grasping. We extended this optimization from simple symmetric grippers to a more anthropomorphic thumb-index finger configuration. This included additional input design parameters, including allowing for differing kinematic properties, link lengths and initial starting angles for the thumb and forefingers. The heuristics used to evaluate a favorable precision grasping were grasp stability, post-contact system work and the range of object sizes that can be stably grasped. This was to determine if a given thumb-finger pair could stably grasp a variety of objects from a single actuator with a given actuator maximum torque. As an additional step of the evaluation, we selected a subset of favorable kinematic configurations and loaded them under external wrenches to determine the maximum resistible wrench each configuration could handle. This step evaluated the objects ability post-grasp to stay within the hand if additional forces were applied to it.

Given our initial asymmetric model, 0.008% of tested configurations (n = 28.8 million) remained stable for an object

size of 0% to 50% finger length assuming the generated thumb provided contact and stability. We attribute this lower percentage of stable configurations for the asymmetric testing to two factors. First, given the anthropomorphic constraints on the forefinger, generated thumb and palm width, many configurations did not have a feasible thumb inside the kinematic constraints to match the sampled forefinger. Second, some of the simulated "objects" had too large of an initial tilt – due to large variance in the forefinger and thumb instantaneous velocity – leading to slip in the hand-object system. The simulated friction coefficient for both simulations was conservative at  $\mu = 0.7$  or an equivalent of a 90° angle about the contact point.

The mean and optimal link length ratio for a stable asymmetric configuration were fairly close being low for the forefinger (opt =  $0.682 \ \mu = 0.831$ ) and slightly higher for the thumb (opt =  $1.1 \mu = 1.09$ ). We found that these aligned fairly closely with the index PIP joint location and thumb IP joint location in human hand [24] with the index proximal link being slightly shorter and the thumb proximal link being slightly longer. The generated thumb was also recorded to be slightly shorter (86.5%) on average than the sampled forefinger with a normalized length. We believe the asymmetric joint locations vary from each other and the symmetric solutions due to the varying initial angle constraints  $(\theta_{Fi}, \theta_{Ti})$  for the asymmetric testing. We must note that due to the complexity of human finger actuation we did not expect our single actuation model to reflect anthropomorphic solutions that were favorable. Solutions did exist across most joint locations, however, our optimal solution did have a joint location similar to that of the human hand.

For the asymmetric configurations, the mean transmission ratio, the ratio between the distal and proximal tendon radius, was rather low for both the forefinger ( $\mu = 0.233$ ) and thumb ( $\mu = 0.054$ ). These low values are representative of the larger required finger joint angles to contact a given size object when compared to symmetric. This is because the starting angles widened the initial finger span relative to the symmetric case requiring additional motion to grasp objects of a given size. This finger configuration requires the equilibrium point to be closer to the joint for the system to remain stable. Variations in object tilt and joint location required the forefinger equilibrium point to be further from the joint than the thumb to provide a viable grasp.

The stiffness ratio, which was determined from an anthropomorphic free swing trajectory for a given transmission ratio, created larger motion envelopes  $(\Delta \theta_p \gg \Delta \theta_d)$  given the found transmission ratios for the asymmetric case. This included a very high mean stiffness ratio for the forefinger ( $\mu = 3.585$ ) and thumb ( $\mu = 13.35$ ). We believe that this was to balance the motion from the relatively low transmission ratios for both fingers. The palm length for the asymmetric case. This is because a larger range of motion with a fixed anthropomorphic free swing trajectory caused the instantaneous velocity of the fingers to displace laterally instead of palmar and laterally in the symmetric case. The top configurations were then determined through a heuristic evaluating their ability to stably grasp across their entire grasp span with minimal post contact



Figure 5. Results from the asymmetric simulation showing (left) the minimum resistible wrench for the top 40% of heuristically optimal configurations where percentage indicates how many of those configurations can exist a given force in the X and Y directions. (middle) The post contact reconfiguration of the thumb and forefinger including the object reconfiguration and equilibrium point reconfiguration. (right) The simulated and experimental wrench resistibility of the heuristically optimal configuration that are used for the prosthetic hand.

work. Those top 40% were then subject to additional testing to determine an optimal choice for the prosthetic hand.

The top 40% favorable configurations within the anthropomorphic range were evaluated when exposed to external disturbances. These configurations were identified to have very little object and finger reconfiguration during object acquisition and post contact (Fig. 5). When compared to the symmetric study, asymmetry in general provided a substantial increase in resistance to external disturbances when an object is grasped. This included for the same applied wrench and object an increase of the 50<sup>th</sup> percentile of configurations from 1.3N with symmetric to 3.2N with asymmetry. This included a large increase from the optimal symmetric (1.9N) to the optimal asymmetric (4.1N) configuration (Fig 5.).

The maximally performing configuration that remained stable and minimized post-contact work for a variety of object sizes was locally sampled for additional resolution returning the final kinematic properties displayed in Table 1. These final parameters were transferred to the final prosthetic hand, assuming a maximum proximal joint stiffness of  $K_p = 0.044 \frac{N}{m}$  representing the max feasible stiffness of an off the shelf torsional spring that fit our 50<sup>th</sup> anthropomorphic female hand dimensions. After establishing the final parameters, we evaluated this kinematic configuration in both simulation and experimentation to see if it is stable to a variety of external wrenches.

We found that this configuration was even more stable than the symmetric option found in the symmetric study [21]. The asymmetric simulation provided a stable resistance of approximately 15.8 N in the +X direction, 10.4 N in the -X direction, 4.1 N in the +Y direction and 10.2 N in the -Y direction (Fig 5.). The physical testing of a gripper with the given kinematic parameters provided a stable resistance of 12 N in the +X direction, 10.5 N in the -X direction, 6 N in the +Y direction and 7 N in -Y direction. The minimum resistible wrench of the simulation was 4.1 N compared to 5.9 N for the experimental evaluation. The average error between the simulated and experimental asymmetric results was 15.8%. We believe this error was decided from the gripper slightly outperforming the simulation in the +Y direction. We believe that both the symmetric and asymmetric error is still fairly low given the simplification of the hand-object system in our model. The full resistible wrench results are displayed in figure 5.

In these precision grippers, we found that the x-direction provided more nominal resistance to external disturbances with slight increases in the Cartesian orientations opposite of the post contact reconfiguration. This intuitively makes sense as the gripper may be more compliant in these orientations. When planning to manipulate an object, it is favorable to know the direction of maximum force resistance so the operator can orient the gripper such that external loading is applied in the direction of maximal disturbance resistance or so that gravity is optimally resisted. This can be increased by either increasing the minimum resistible wrench or by tweaking design parameters to better fit a given grasping or manipulation task.

## B. Geometric Optimization Study

To establish the finger pad and palm geometry we followed guidelines from our previous research on developing effective soft finger pad geometries [26]. In this paper, we experimentally examined the frictional behavior of several common primitive contact geometries to evaluate their performance in a grasping context. This was done by evaluating the effective coefficient of friction at a variety of loads and establishing a power law coefficient for each of the primitive geometries: a cube, a sphere and a cylinder. Each primitive geometry was evaluated at three different contact areas which were normalized for each geometry. To model the frictional response of these structures we used a deviation of Admontons' laws of friction that displays the nonlinear variation in friction with loading for elastic structures. In materials such as silicone or urethanes, tribological literature describes the coefficient of friction as nonlinear, following a negative power law [27][28].

$$\mu$$
Static =  $a$ (FNormal)<sup>*n*-1</sup>

Where a and n are constants and the coefficient of friction has a nonlinear and inverse relationship with the applied load on a given elastic finger pad surface. With this equation we were able to model the frictional response of finger pads of



Figure 6. Examples of the hand grasping the two sensor embedded objects to determine the grasp force in each of the three grasp types. We used a two-inch sphere with a uniaxial load cell to evaluate power grasp force (A) and we used a one-inch cube with a uniaxial load cell to evaluate tripod (B) and lateral (C) grasp force.

varying geometries under a load range seen commonly in human and robotic grasping.

For the first alteration to our finger pads, we found that curvature matching, or equivalently an even pressure distribution, is incredibly important especially at low contact forces. This made us flatten our distal fingertip where we believe flat objects will contact in tripod grasp and then round locations where we observe rounded or cylindrical contact on the outer edges. We found that this is also consistent with the human fingertip which is not purely cylindrical but more of a rounded rectangle. Additionally, we extended the distal finger pads to below the metal finger nail and flattened this geometry. This is because we were having issues grabbing small flat objects like a coin, washer or credit card. This extension promoted soft contact on these small flat edges and also provided support with additional contact points under the fingernail.

Next when we extrapolate our testing to practical prosthesis, most hand-object configurations rely on several contacts to produce a viable grasp. This usually consists of several line or point contacts with fairly cylindrical or rectangular prosthetic fingers. It is therefore best practice to attempt to increase the radius of the finger pad at regions of expected contact assuming the object is convex. This is because line a point contacts with effective zero-radius contact region will produce an unfavorable surface area and holding force leading to object slip. We recommended that the proximal finger pad areas that are expected to be in contact in power or wrap grasp be flat in opposition, for flat or rounded objects, then rounded off with the largest radius possible to avoid point and line contacts for non-flat objects. These rounds also help provide extra contact area for objects that may slide between the fingers because of irregular geometry, smaller geometry, or a misaligned grasp. The finger pads were flattened and extended in critical areas around the medial and lateral sides of each finger to fasten or grasp objects that have geometry that fits between the fingers.

## IV. TESTING METHODS AND RESULTS

In this section, we will discuss how we evaluated our single actuator myoelectric hand and present our kinematic specifications and results. We had two primary ways of evaluating the device. First, bench top testing was completed to evaluate the general performance and specifications of the prosthetic hand. This was also to ensure the hands performance aligns with the specifications necessary for these devices outlined in previous literature. Second, a ten participant ablebodied study (P1-P10) evaluating the hands repetitive motion, learning curve and performance on activities of daily living. For the prosthesis, participants wore an able-bodied simulator (TRS Prosthetics) that is designed to help able-bodied users simulate prosthetic use. This device includes a soft cast with a distal mounted prosthetic hand adapter. Two transradial amputee participants (T1,T2) also completed the study using their preexisting prosthetic sockets. The participants actuated the hand using a single external button that both opened and closed the hand. These testing methods were kept consistent to our evaluation of the preliminary version of this hand for comparison after optimization.

#### A. Kinematic Specifications and Benchtop Testing

First, general kinematic specifications such as grasp aperture and force output in each grasp type were measured. Grasp aperature was measured using a digital micrometer from the distal opposing surfaces - fingertips for power/tripod and the thumb contact point for lateral grasp. These apertures were 132.5 mm in power grasp, 125 mm in tripod grasp and 52.5 mm in lateral grasp. These grasps were slightly larger than the previous version of the hand (113.8 mm in power/tripod and 15.4 mm in lateral) due to the widening of the initial angle of the thumb from the kinematic optimization study. The slight change in aperture in power and tripod are due to slight adjustments in the pre-tensioning in tripod grasp to keep its closing speed consistent. We believe these larger apertures, coupled with spring stiffnesses to speed the hands closing rate, provided a larger array of possible objects to grasp with minimal proprioceptive loss while grasping.

TABLE II.BENCH TOP TESTING RESULTS

Grasp Type	Grasp Specifications			Average Angular Closing Rates (°/s)			
	Grasp Force (N)	Close Time (s)	Grasp Width (mm)	FF MCP	FF PIP	T MCP	T PIP
Power	14.3	1.02	132.5	92.9	78.2	29.3	48.9
Tripod	5.0	0.53	125	149.9	74.9	9.4	131
Lateral	17.2	0.60	52.5	0 (fixed)	0 (fixed)	41.5	116



Figure 7. (Top) The test set up for able bodied participants including (A) the button for manually opening and closing the hand (B) the test currently being evaluated (C) the prosthetic hand (D) the able-bodied adapter (E) control electronics. (Bottom) example of an able-bodied participant completing a SHAP task with the prosthesis.

In [29], the recommended closing rate for a tripod grasp should not exceed 0.8 seconds with a span greater than 90mm to have minimal effect on proprioception. In [30], adequate full closure of the hand in any grasp should be from 1 to 1.5 seconds. Our tripod grasp falls within dictated specifications in [30], however, it may be advantageous to increase the speed of the power grasp which falls outside this recommendation but within those in [29]. We believe that these speeds are adequate, with minimal proprioceptive interference, given the changes in kinematics and increase in grasp aperture.

Additionally, using a digital protractor the angle limits and hardstops were recorded and then divided by the closing rates to produce estimates for the average angular closing rates before contact. We must note that these are not linear but averages of the speed across the closing rate. Although none of these closing rates are near the performance of the human hand, near  $300^{\circ}$ /s, it is rare to see human finger angular velocities exceed  $100^{\circ}$ /s during grasping [7]. For our force production ranges we believe that our grasp types nearing  $100^{\circ}$ /s are acceptable. These results are examine further in the table 2.

Next, grasp force was evaluated for each grasp type using custom sensor embedded objects that we believe were representative of how that grasp will be used on activities of daily living. For a fair comparison, we used the same actuator with the same gearing (Faulhaber MCDC 3002S) and the same sensor embedded object sizes (2.5 in sphere in power and 1.5 in cube in tripod/lateral), positioning and load cell (Transducer Techniques MLP-25) seen in figure 6. Additionally, the same grasp dynamometer was used (Camry EH101 Digital Dynamometer) to establish power grasp force in a more comparable manner. The average maximum grasp force using the sensor embedded object in power grasp was 14.3 N in power grasp, 5.02 N in tripod grasp and 17.2 N in lateral grasp. The grasp dynamometer produced 17.9 N of force in a 2in grasp span power grasp. First, we found that the force output was lower that the previous version in power and tripod grasp by 1-2 N. We found that this decrease in force occurred because the optimization was based on grasp stability and not directly correlated to grasp force. The best performing hand does not necessarily have the highest grasp force. For example, a hand with high relative grasp force with misalignment at the area of contact can produce more shear forces leading to ejection of the object. We can contribute our better performance in activities of daily living in the next section to the kinematic structure of the hand which although with less force production in these grasps provided more stability across a range of objects. The hand performed slightly better in tripod grasp 5.02 N compared to 3.56 N because the frictional losses have a greater contribution at low forces. The final version of the hand more effectively transferred force in this grasp type with slightly less frictional losses in the new transmission gearbox and backplate. We believe that if these were kept similar there is a change this grasp type would have fairly similar or even less force production. Last the grasp dynamometer force production was fairly similar 17.9 N compared to 19.6 N previously. We believe that this loss is similar in explanation to the power grasp that hand slightly less force production after the kinematic stability optimization.

#### B. Human Participant Study

In this section we will discuss our human participant study under IRB (ref#1608018242) where we tested ten able bodied participants (n=4 females, n=6 males, avg. age = 26.3) performing abstract object tasks and activities of daily living. Two tests were performed twice by each participant, once with their able dominant hand and once with the prosthetic device. This choice was to normalize their prosthetic scores with their able body scores to determine relatively how effective the prosthetic is at performing everyday activities. The first test was the Box and Blocks test that evaluated repetitive motion. This test included three trials of moving 1 in cube blocks over a barrier for sixty seconds. The second test was the Southampton Hand Assessment Procedure (SHAP) [31] which evaluates the

TABLE III. HUMAN PARTICIPANT STUDY RESULTS

	Prosthetic Device							
Test	Yale	ETH	DMC	Michelangelo	i-Limb	i-Limb Pulse		
Box and Blocks	19.1	16	16	24.5	NA	NA		
SHAP	82	58	51	82	52	88		

Difference in Able-Bodied and Prosthesis Box and Blocks



Figure 8. Comparison between the number of blocks successfully grasped for each participant's able hand and the prosthesis. The percentages displayed show relatively how effective each participant was at grasping blocks with higher percentages displaying favorable performance with the prosthesis.



Figure 9. Examples of objects grasped in (left) power grasp displaying grasp adaptability (middle) tripod grasp displaying the distal finger pad contact for larger objects and finger nail contact for smaller objects and (right) lateral grasp displaying the passive hook grasp and active lateral opposition grasp.

hands abilities to quickly complete activities of daily living. This consists of twelve abstract objects tasks and fourteen activities of daily living such as pouring, using a zipper, or turning a page. The goal of this test is to encourage the participant to complete a given task as fast as possible by pressing a timer, completing the task and then stopping a timer. The results of this test are graded on a scale of 100 where 100 is comparable to unimpaired hand function. The test setup and an example of a participant completing a SHAP task can be seen in figure 7.

In the box and blocks, the able-bodied participants scored an average of 19.2 blocks ( $\sigma$ =2.17, high=23, low=15) blocks over the barrier in sixty seconds when compared to an unimpaired  $\mu$ =59.1 ( $\sigma$ =5.37, high=67, low=52). The average blocks missed while completing a task with a prosthesis was 3.1 blocks average over the course of the trial while with the normal hand a block was never missed during a trial. Outside of unsuccessful grasps, we found the prosthesis users took additional time planning where to grasp. We observed users selecting the nearest block or picking from the middle when using their able-bodied hand, whereas with the prosthesis users attempted to find blocks that were isolated. In the amputee participant study, T1 scored an average of 12 blocks over the barrier with the MyoAdapt hand and an average of 23 with their current iLimb hand. T2 scored slightly better with our hand, averaging 16 blocks over the barrier with our device and 23 blocks over the barrier with their Taska Hand. We found that it took both participants a little bit of time to familiarize with using the button for control.

Other feedback from this testing includes that the lack of manipulability of the prosthesis, including the ability to quickly reorient a block or regrasp a block in a cluttered environment, may lead to more failures or added time to correctly place the hand. Participants that pre-grasped, effectively decreased the aperture of the grasp by prematurely closing before the grasp, had significantly better results. We found all participants were roughly in the same range of average blocks picked with the prosthesis with percentage variations being influenced by how quick they were with their able bodied hand. The maximum we observed was 40% of able-bodied blocks picked with the prosthesis and the minimum we observed was 26.3% of ablebodied blocks picked with the prosthesis. In the future, we would like to see if the control tradeoff of adding manipulation or aperture adjusting abilities in the control can feasibly increase a prosthetic hands ability in this test. The full results are seen in figure 8.

In the SHAP test, the participants scored an average of 83.7 Index of Function or IoF ( $\sigma$ =4.00, high=90, low=78) with the prosthesis when compared to an average 97.5 IoF ( $\sigma$ =2.72, high=103, low=94) with the participant's able hand. Using the prosthesis, we found difficulties in the tip and tripod tasks with averaging around 75 IoF compared to the able hand averaging 95 IoF. In the amputee participant study, T1 scored a 55 total IoF with their iLimb device performing best in the lateral grasp tasks (74 Iof) and worst in Tip grasp tasks (33 IoF). T1 scored slightly lower with the MyoAdapt hand scoring 44 total IoF and performing best in Spherical grasp (70 IoF) and worst in Tip and Tripod grasp (26 IoF, 24 Iof). T2 scored a 62 total IoF performing best in the Spherical grasp tasks (84 IoF) and worst in the Tip grasp tasks (32 IoF). With the MyoAdapt hand T2 scored a 60 total IoF producing an average amputee participant IoF of 61 T2 performed best in Spherical grasp tasks (83 IoF) and worst in Tip grasp tasks (28 IoF).



Difference in Able-Bodied and Prosthesis Index of Function

Figure 10. The difference between each participant's able-bodied score compared to their prosthesis score for each SHAP category. Each increment represents approximately 1% of human hand function with smaller differences indicate favorable performance by the device and larger differences indicating unfavorable performance by the device in each given category.

After testing, we found that our hand performed better than the previous version, however, still lacked in tripod/tip grasp. We observed that grasps in tripod/tip were approached similarly with the prosthesis than with the able-hand or current prosthetic device, however, we found that participants lost significant time post-grasp attempting to replace the object. This was seen especially when an object was grasped further away from its center of mass causing post-contact rotation of the object in the hand. While underactuation, especially with differential mechanisms, aides force distribution and contact stability we believe kinematic improvements can still be made to further refine the hand. In the future, we believe integrating off-center center of masses relative to the antipodal points in our optimization framework can improve the kinematics and grasping stability of the hand. The prosthesis performed the best on the spherical tasks which averaged 90 IoF for able-bodied and 77 IoF for amputee participants. We believed that this result was excellent for our prosthesis and found that most of the time difference was accounted for the time to open or close the hand relative to the able-bodied hand. Some examples of successful grasps representative of activities of daily living can be seen in figure 9.

Last, no test is perfect and during human participant studies it is hard to evaluate a device without evaluating the user's ability. We found that in every bilateral task, results with the prosthesis were slowed from having to move from the task to the driving button and then back to the task. Additional time was observed on each task when attempting to move to and from the timer. The user's ability to located and correctly hit the button or timer greatly influenced their final score.

## V. DISCUSSION

# A. Testing Results

In the benchtop testing, we found the change in hand kinematic parameters displayed favorable results when compared to the previous device. This is including a widened aperture, and thus range of motion, in all three grasps by around 20mm with similar average angular closing rates. Because prosthesis have not approached the potential of the human hand, improvement in grasp range of motion and speed is a positive contribution when creating anthropomorphic hands given there is minimal force tradeoff. In underactuated systems with a single actuator and simple transmission, there exists an inverse relationship between grasp force and grasp speed. This tradeoff in the MyoAdapt hand included around 14% average increase in closing rates with around a loss of 1% of average grasp force across all grasp types. Given the increase in grasp aperture and average angular closing rates we found only slight changes in force production. This included an increase in precision grasp force from the optimization with only slight decreases in force production in power and tripod. We believe that the slight decrease in power and tripod is an artifact of improved design of the transmission mechanisms in the hand which more efficiently transferred torque from the motor to the fingers including the integration of friction reducing mechanisms in the whiffletree mechanisms and gearbox. We found that having unique grasp types such as a slower and stronger power grasp and a faster more delicate tripod grasp helped us navigate this tradeoff for a variety of situations. This includes having the force production to grab a heavy sphere but also have the speed to quickly grasp and regrasp small blocks, coins or buttons.

In the human participant trials, we found improvements in reported scores for the Box and Blocks and SHAP test over the initial prototype. In the Box and Blocks the final prototype scored an average of 19.2 blocks with 2.17 blocks missed and





Figure 11. The full SHAP test profile for each amputee participant, including device data from the Yale MyoAdapt hand (device a) and their current prosthetic device (device b).

the initial prototype scored 19.1 blocks with 3.7 blocks missed. Although this increase isn't substantial, we found the increased aperture in tripod grasp made the hand slower at grasping blocks. However, we believe the added stability bolstered the ratio of blocks that were successfully grasped. This is interesting because we found you can slightly increase scores on this test simply by reducing the amount of blocks dropped. If we were to repeat this test with larger blocks we would expect our hand to perform even better because the change in aperture may have less of an effect. In the SHAP test we found that our average index of function of 83.7 over the previous index of function was 82.0. Although this seems like only a slight improvement, this represents a 17 second gross improvement on the entire test which aggregates to around 150 seconds for an 82. Next, our kinematic optimization was created to focus on the low scores received on the previous devices testing specifically in the tripod ( $\mu$ =74.2 IoF) and tip ( $\mu$ =50.2 IoF) categories. The final version improved significantly on these tasks including a 71.4 IoF in tip and 77.8 IoF in tripod. We found that users had significantly less time required to successfully learn the task before completing a timed trial. This includes additional stability on the heavy objects being grasping in tripod. We noticed that the extended grip pads significantly helped for the tripod grasping abstract object tasks and thin objects such as the page and coins. We also saw minimal change in the performance in power grasp activities even with the slightly decreased power grasp force. We believe this can also be attributed the additional friction and more effective force transfer from the changes in fingerpad geometry.

When comparing participants able-bodied IoF to prosthesis (Fig. 10) we found that participants performed nominally the best on spherical grasp tasks and the worst on tip grasp tasks. In spherical grasp we found participants were only 10 IoF or approximately 10% worse than using their able-bodied hand whereas in the tip they were approximately 27 IoF or 27% worse than their able-bodied hand. All the other grasp types evaluated in the SHAP had participants that either performed very well (<10% from able-bodied) or very bad (>25% from able bodied). We would describe these tasks as user dependent

and we believe these could potentially be improved with increased training time. Additionally, we had two participants where almost all categories were within 10%-15% of their human hand function which we believe is incredible for a prosthetic device given minimal training. We found these participants, were more likely to approach grasping an object in a different way they would with their normal hand. We believe this creativity, which is necessary for grasping abstract objects with most simple prosthesis, is still beneficial for anthropomorphic devices. Last, we had two participants struggle, specifically when using the hands tripod grasp. This not only talks to the difficulty of grasping small objects like coins with anthropomorphic devices but also to the room for improvement there still is in precision grasping with underactuated devices.

## B. Comparison to Commercial Devices

When compared to a single actuator robotic split hook in [32] (Motion Control ETD Proplus) our hand performed 37.1% better on the Box and Blocks and 44.3% better on the SHAP test. When compared to a single actuator anthropomorphic robotic tripod grasper [32] (Ottobock Transcarpal DMC Plus) our hand performed 37.1% better on the Box and Blocks and 64.1% better on the SHAP test. Although all the devices have a single actuation input, the relative increase in performance on the SHAP test, focused on activities of daily living, could have been bolstered by the ability to have more than one grasp type. This would provide less of a benefit on the SHAP test where a simple split hook and tripod grasper could suffice. In both evaluations the wrists were secured in their neutral positions. In [32] amputee subjects with significant training used myoelectric control while in our study a mechanical button was used for able bodied testing. We believe that novice users with a button would provide only a slide advantage, if any, over a trained prosthetic user.

When compared to a two actuator anthropomorphic robotic prosthetic hand [33] our hand performed 31.4% worse on the Box and Blocks and similar on the SHAP test after three months of practice. When compared to a fully actuated five actuator anthropomorphic robotic hand [34] (Ossur Touch Bionics i*limb*) we performed 61.0% better on the SHAP test after one month of practice and 10.1% better after one year of practice with the i-Limb device. Compared to the newer device (Ossur Touch Bionics i-Limb Pulse), our hand performed 5.9% worse after one month of practice and 3.8% worse after four months of practice with the device. With a static wrist our hand had similar results in the SHAP over the two actuator hand, however, lacked in the Box and Blocks. This could be due to our single actuator hands weak precision grasp compared to the Michelangelo's two motor precision grasp and the significant training time allowed for the participant. Minimal grasp variety in the Michelangelo hand could have been a negative component to the overall index of function. Compared to the five actuator hands our hand performed favorably against the i-Limb and slightly worse than the i-Limb Pulse. Although there is only one participant in [34], he had the ability to actively flex and extend his wrist which could provide a benefit in the SHAP test for complex motions. All amputee subjects in [33][34] had significant training with myoelectric control and should have provided minimal benefit over the button.

The weight of the Yale MyoAdapt Hand with threaded socket adapter was 380 grams making it slightly less than the 410 gram weight of a 50<sup>th</sup> percentile human hand [24]. This hand was also lighter than commercial prosthesis including the i-Limb (443-515 grams), the Bebionic Hand (550-598 grams) and the Michelangelo hand (420 grams). Further weight reduction could be considered in the Myoadapt hand especially in optimization of the finger and palm chassis structures.

When comparing our amputee participant study to their current devices we found that performance was comparable, but slightly worse, then the current devices the participants were using. T1 scored 20% better with their current iLimb device on the SHAP test compared the MyoAdapt hand summing to an 11 point difference in index of function. In post study feedback, T1 noted that the device got easier after completing a decent amount of the tasks and may have required additional training time (maybe an hour versus the ten minutes allotted) to familiarize better with the button control and hand. The participany liked that some of the more difficult tasks to complete with their current device were easy with this device and minimal training. This included the MyoAdapts lightweight, responsiveness and aperture compared to her current device. The task that T1 found most difficult was the zipper task which requires a significant amount of pinch force that the MyoAdapt and iLimb did not have. T2 scored 3% better with their current Taska hand with active wrist and pattern recognition, summing to a two point difference in index of function. In post study feedback, T2 noted that they liked the hands wide aperture and ability to grasp round objects in power and tripod grasps. They enjoyed the finger dexterity and the ability to fixate objects within the hand and between the fingers. They found that the hardest task to perform was the coins, which is harder to complete with complaint rather than rigid fingers, and would like the hand in the future to have an active wrist to make adjusting for objects easier. We found that T2 was able to guickly adjust to the new device and control method for the MyoAdapt hand.

We displayed that through novel underactuated mechanism design and leveraging multiple grasp types, you can create a prosthetic hand that is similar in functionality to hands with complex control and multiple actuators. We also found that optimizing the kinematic and geometric parameters of a hand given identical power, control and transmission - can lead to better performance on repetitive tasks and activities of daily living. Last, we believe the MyoAdapt hand is a convincing argument for single actuator underactuated prosthesis. An underactuated anthropomorphic hand driven by a single actuator provides the benefits of simple control, passive adaptation and reduced weight that is favorable for many amputees [1]. There is currently no hand that can mimic the functionality of the human hand, however, as control and hand complexity improves we believe the MyoAdapt hand alongside other underactuated hands - can serve an important purpose. We believe that a hand with mechanical complexity and simple control can be a great launching pad with people who are new to amputation and can make a stepping stone to familiarizing themselves with upper limb prosthesis.

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