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Comparative Clinical Evaluation of the Yale Multigrasp Hand

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***Abstract*—While the functionality of myoelectric prosthetic hands continues to increase, body-powered terminal devices continue to be preferred by upper-limb amputees. Until now, the ability to achieve various grasp types in an anthropomorphic hand has been exclusive to myoelectric hands. The Yale Multigrasp Prosthetic Hand, a novel anthropomorphic multi-grasp body-powered terminal device, was designed and tested for use as an upper-limb prosthesis. The functionality of the Yale Multigrasp Prosthetic Hand was evaluated through benchtop testing and a twelve-subject able-body study. One unilateral trans-radial amputee and one bilateral trans-radial amputee performed evaluation studies to determine the level of dexterity achieved with the hand. Results show comparable performance to current commercially available terminal devices on both the Box and Blocks and Southampton Hand Assessment Protocol.**

Keywords*—Prosthetics, body-powered, underactuation, 3d printing, prosthetic hands, prosthesis evaluation, compliant, passively adaptive

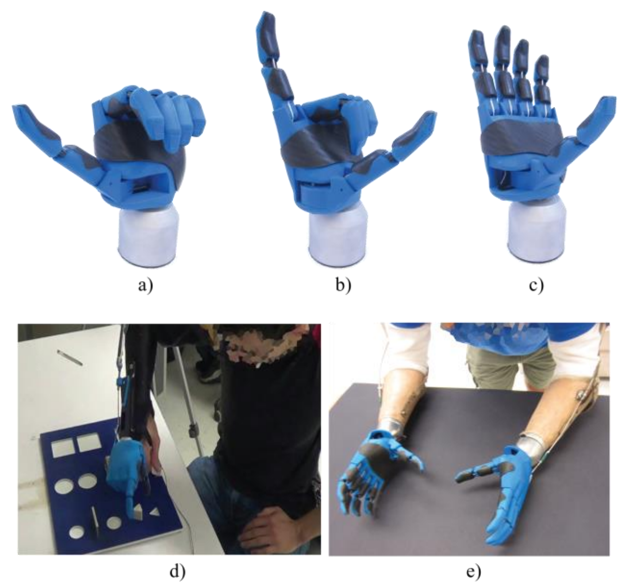

Fig. 1. The Yale Multigrasp Hand features lateral (a), precision (b), and power grasps (c) all actuated through a single body-powered cable. The grasp type is selected through a simple movement of the thumb. The hand was evaluated by able body subjects, (d) as well as amputees (e).

I. Introduction

Over the past 10 years there have been numerous robotic hands developed in research labs with the intent of being used by amputees as a prosthetic hand [1-4]. Many of these take advantage of multi-degree of freedom actuation and more advanced control strategies to interpret user intent. In electric devices, the prosthetic hand is actuated by one or more motors that is controlled by electrical activations from the user's muscle contractions. Electrodes pick up the signal and interpret the signal to open or close of the prosthetic hand. More complex electric devices can use multiple electrodes and pattern recognition, a logical connection of multiple contraction signals or patterns, to perform different grasp types based on the combination of muscle contractions. A more traditional approach to prosthesis actuation is through a single body-powered cable. The cable is mounted to a harness that the user can manipulate to drive the closing of a simple grasper. More recently, coupling mechanisms have been integrated into body-powered hands to produce anthropomorphic multi-grasp hands with more complex movements and grasp capabilities [5].

When a prosthetist is choosing a terminal device for an upper-limb amputee patient, they have a choice between body-powered and electric terminal devices. Prostheses can range anywhere from complex electrically actuated hands to purely cosmetic passive hands that have similar texture and appearance to real hands. Body-powered systems provide more options to fit an amputee patient's specific needs. When it comes to upper-limb amputee preference, they prefer body-powered over electrically powered terminal devices due to their durability, reliability, proprioceptive feedback, and low cost [5]. However, body-powered hands tend to have one degree of freedom in grasping, yielding only one grasp type. This makes the users have to manipulate the hand or make compensatory movements to achieve different grasps. Electrically powered devices attempt to improve the functionality of upper-limb prosthetic devices by adding more grasp types, allowing users to accomplish more daily activities. These electric hands nominally boast an anthropomorphic and polished appearance compared to their body-powered counterparts.

At the Yale GrabLab, we have developed a low-cost body powered anthropomorphic prosthetic hand that bridges the gap between body-powered and electric hands by incorporating the advantages of multiple grasp patterns achieved through myoelectric hands. We chose to develop a body-powered system because it gives the users proprioceptive force feedback when grasping, requires purely mechanical control and improves on overall system robustness because no electrical components are required. Our hand is multi-grasp and through a simple movement of the thumb, the user can select between a power, precision, or lateral grasp (see Fig. 1a-c). The single body-powered cable drives all three of the hands grasps, however, the force

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distribution for each finger varies depending on the grasp used. We believe that our novel prosthetic hand can retain the durability, reduced cost and weight, and proprioceptive feedback of a body-powered split hook while encompassing the multi-grasp functionality and aesthetic appeal of more complex robotic hands. In this paper we set forth to evaluate our hand versus other hands currently on the market. This was accomplished through comparative functional testing of our hand and a professional body-powered anthropomorphic terminal device, the U.S. Army Prosthetic Research Laboratory (APRL) VC Hand and the Hosmer Dorrance 5X Split-hook Terminal Device (see Fig. 2). This testing aimed to get a qualitative measure of hand function, however, the standardized tests used in any study nominally cannot accurately capture the dexterity and the manipulation ability of the hand.

For our comparative evaluation, we chose the Box and Blocks (BBT) [6] and the Southampton Hand Assessment Protocol (SHAP) [7] measures of functionality due to the simple quantitative scoring metrics and the incorporation of both dexterous quick movements and activities of daily living (ADL). We present benchtop test performance specifications for each terminal device as well as present the results of both an able-body and amputee clinical study. User feedback was also collected and analyzed to evaluate user preference and additional uncaptured factors.

II. The Yale Multigrasp Hand

The Yale Multigrasp hand was developed as a body-powered replacement for multi-articulating myoelectric prosthetic hands. The hand's geometric dimensions are based on the 50% female hand size. The body-powered cable forces and travel are consistent with commercial terminal devices including both hands and hooks. One of the major advantages of the Yale Multigrasp hand is that the three grasp types utilize the same actuation through a single body powered cable (see Fig. 1a-c). The positions of the thumb act like a transmission to change the grasp type of the hand, which also alters the forces, and timing of closure of the fingers which is optimized for each grasp type. The hand also features a standard ½"-20 threaded post, the standard wrist attachment method for body powered terminal devices.

The fingers of the Yale Multigrasp Hand are differentially coupled to the main input tendon that provides an adaptive underactuated grasp on objects. This behavior greatly improves on the hands ability to passive conform to various object sizes and to increase the number of contact locations formed by a single pull of the body powered cable. The passive abilities incorporated mechanically into the hand remove some of the user's cognitive burden when trying to grab and manipulate objects.

The Yale Multigrasp Hand is an anthropomorphic voluntary closing hand that has five individually adaptable fingers. The hand has three grasps, a wide power grasp, a precision grasp, and a lateral grasp that can also be used as a passive hook grasp. In precision grasp, the index finger opposes the thumb and grasp force is shared equally between the two fingers while the other three fingers are locked in the closed position. In lateral grasp, the thumb swivels to oppose the side of the index finger and all grasp force is diverted to the thumb. The other four fingers are locked in a partially closed "hook" position which is often used to lift or carry object in a similar way to how a passive hook may be used. The hand has urethane grip surfaces to allow for more stable grasps as well as plastic finger nails to pinch very small objects such as coins or credit cards from a table surface.

Fig. 2. The Yale Multigrasp Hand (a) was compared against the popular Hosmer Dorrance 5X split-hook (b), and the APRL voluntary closing hand (c).

Although a few of the transmission and post components are machined from steel and aluminum, most of the Yale Multigrasp Hand is fabricated through 3d printed ABS components. Fabricating the hand with 3d printing allows for customizable hand sizes, shapes, and colors with the option to match the unaffected limb of amputees.

III. Commercial Prosthetic Devices

Majority of amputees prefer body-powered prostheses over myoelectric prostheses due to cost, durability, ease of use, and direct feedback from their shoulder. There are numerous types of body-powered prostheses, varying in appearance and actuation scheme. The most common among body-powered prosthesis is the split hook [8], which is preferred for its general robustness, cost, and functionality. Anthropomorphic hands are common due to their aesthetic appearances, varying functionality, and ability to fit under a cosmetic glove. Task specific prosthesis can also be used at work or in daily life. In the next section, we will introduce the body-powered prosthesis used in this study. A comparison of the terminal devices studied can be seen in Table 1 and in Fig. 2.

1) Body-Powered Actuation

In body-powered actuation, the driving cable runs from the harness on the back of the shoulder along the residual limb and is guided around the elbow onto the prosthetic socket by an assisting strap. The most common method of actuation is to utilize a combination of shoulder movements and upper arm motion to pull on the cable that can either open or close the hand. These methods include extending one's arm and flexing or adducting one's shoulder.

The terminal devices can be voluntary-opening, where the actuation force opens the hand and a spring defines the return and grip force, or voluntary-closing, in which the user applies force to close the device and grasp objects, with springs opening the device. A benefit to voluntary-opening systems is that the user is able to sustain the grasping force for an indefinite amount of time without any additional cable force required after grasp. A limitation to active-opening systems is the grasp force is limited by the spring force making it difficult to control the grasp force on object of various weights and sizes. This is overcome in active-closing systems where the user directly controls the grasp strength, however, the given force has to be sustained by the user for the duration of the grasp. For more information regarding capable cable excursions and forces please refer to [9].

1) Split-Hook

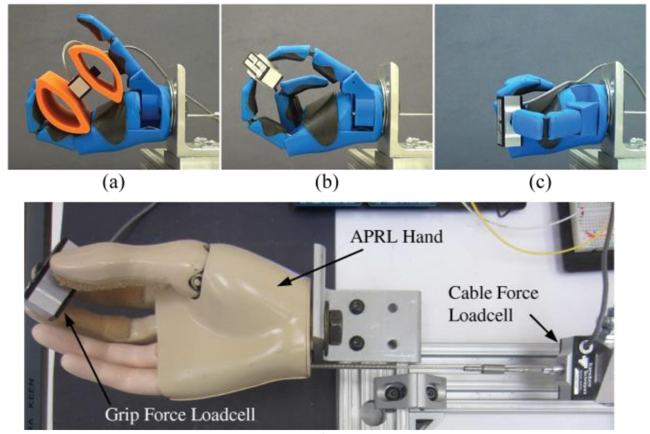
The split-hook device is the most common prosthetic device used by upper-limb amputees. The split hook takes the shape of a normal hook, however, has an additional actuated member that divides the hook profile, see Fig. 2b. This allows for prolonged grasps directed on the hook while also having the fine manipulation of a parallel grasper. A majority of split hook prostheses are voluntary opening where the grip strength is a constant determined by the closing spring mechanism. This force can be altered by either tuning the spring or adding rubber bands to the base of the hook. The specific device we tested was the Hosmer Dorrance 5x Split Hook [8].

2) APRL Hand

The APRL Hand is an anthropomorphic voluntary-closing hand that has two active fingers, the index and middle, and three passive fingers. This hand has two different grasps, a wide power grasp and a tripod grasp, that are made available through a two-position thumb (although the thumb does not move when actuated). The hand also has two grasping methods a pull-to-lock/pull-to-release and a normal voluntary closing. In the pull-to-lock/pull-to-release, a friction lever holds the hand closed at the given position until the cable is pulled again to open the hand. This is convenient for sustained grasps on objects. To remain consistent with the Yale Multigrasp Hand's actuation methods, the locking feature was disabled during the test making the hand function like a simple voluntary-closing terminal device.

Table 1. Terminal Device Comparison

Parameter	Hosmer Split-Hook	APRL Hand	Yale Multigrasp Hand
Weight [gm]	110	345	231
Grasp Span [cm]	9.4 at tip	7.5 thumb out	12.8 power
	-	4.5 thumb in	12.8 precision
	-	-	6.0 lateral
Body-powered Cable Extension	0-44 mm	0-38 mm t-out 0-33 mm t-in	0-48 mm power 28-43 mm precision 28-40 mm lateral
Force to Close (no object)	-	42.2 N	22.5 N
Degrees of Freedom	1	2	11



(d)

Fig. 3: Grip force measurements of the Yale Multigrasp Hand, a) power grasp configuration with the orange grasp cylinder to simulate larger cylindrical objects, b) precision grasp where the grip force is strictly between the index finger and thumb, and c) lateral grasp between the thumb and the side of the index finger. d) The same test performed on the APRL hand.

IV. Benchtop Performance Testing

In this section, we will show the results of benchtop performance testing of the three terminal devices. These tests will include measurements of the body-powered cable force, the body-powered cable excursion, and the grip force.

A. Measurements of Hand Grip and cable excursion/force

The grip strength of each terminal device was tested using a benchtop setup that consisted of a loadcell in line with the actuation tendon as well as a loadcell placed within the grasp. Measurements of grip force were taken at the same input force for comparison purposes. Fig. 3 show the testing setup used to evaluate the terminal device grip forces. The Yale Multigrasp hand had a 42 N grip force in power grasp, a 5.4 N grip force in precision grasp, and a 9.0 N grip force in lateral grasp given a 200 N cable input force, see Table 2.

Table 2. Yale Multigrasp Hand Grip Forces

Parameter	Power Grasp	Precision Grasp	Lateral Grasp
Force at 100 N Cable Pull	23 N	3.1 N	4.7 N
Force at 200 N Cable Pull	42 N	5.4 N	9.0 N

B. Bench testing NIST standards

The National Institute of Standards and Technology (NIST) standard hand tests are often used to evaluate robotic grippers. This set of standard tests focuses on the forces required to pull objects out of the gripper while it is being held [10]. For this testing, the different prosthetic hands were mounted in a fixture with a constant force of 75 N being pulled on the actuation cable. Three different size PVC cylinders (23.7, 42.3, and 60.7 mm outside diameter) were then slowly pulled out of the grasp. The peak load required to completely dislodge the cylinder is shown in Fig. 4 and Fig. 5. The test was performed in both the vertical direction where the fingers of the hand were being forced

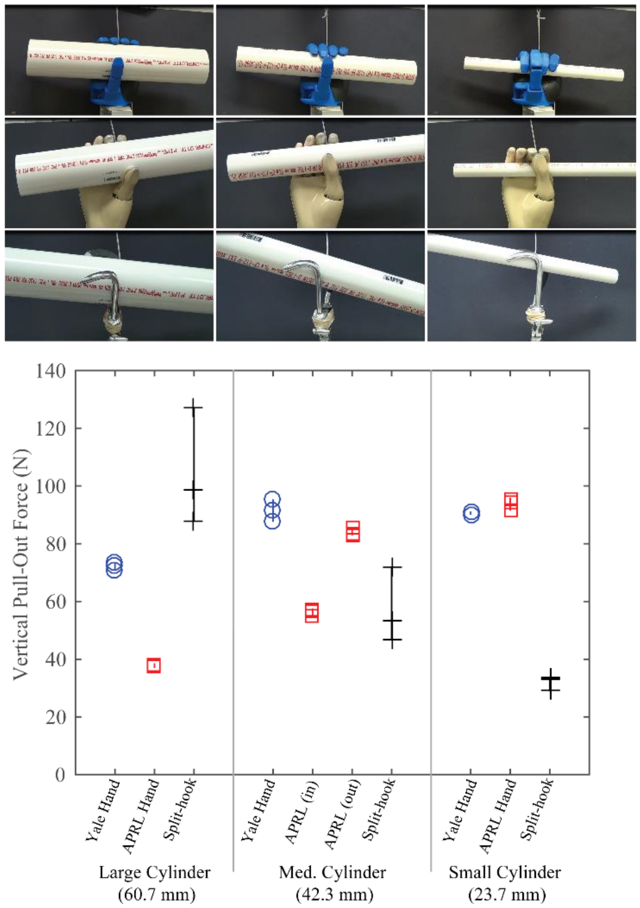


Fig. 4: The vertical pull-out force was measured for the Yale and APRL hands with a constant 75 N input force on the voluntary-closing body-powered cable. The Hosmer Hook was tested with no load on the body-powered cable (the scenario which produced the largest grasp force.

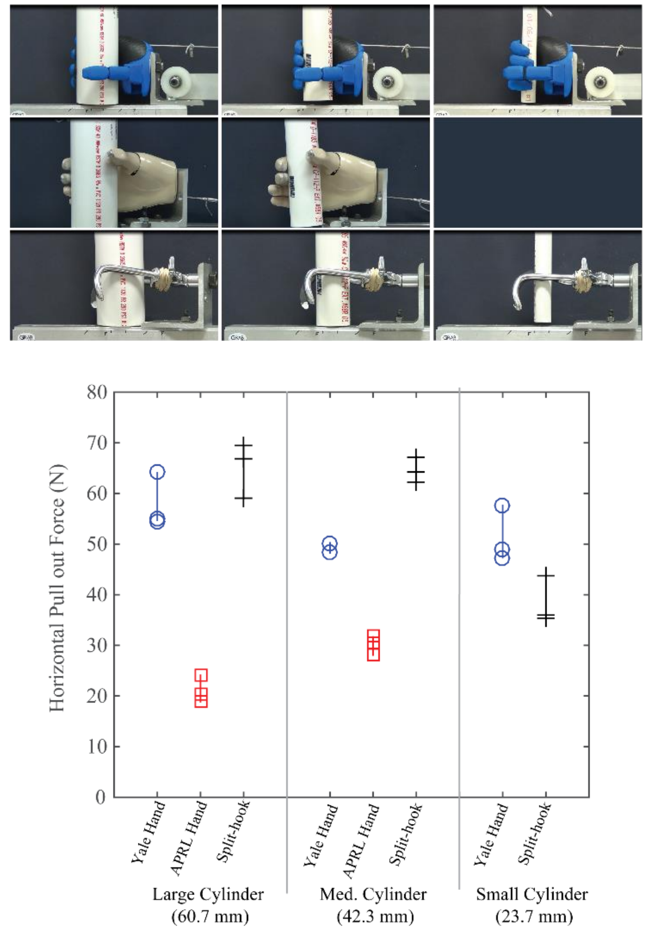


Fig. 5: The horizontal pull-out test was performed by pulling on three different sized PVC cylinders in the direction that slid them out of the grasp from the side (the white cylinders were pulled upward in the images above). This test is similar to the NIST "Slip Resistance" test [10]. Here, images are shown for the Yale Hand, the APRL Hand, and the Hosmer Split-hook. The APRL Hand was unable to close on the small cylinder.

open, and in the horizontal direction where the cylinder was pulled sideways out of the grasp. The horizontal test evaluates both the grip force and the friction of the griping surfaces. Fig. 4 and 5 show that the Yale Multigrasp Hand had a consistent pull-out force for both the vertical and horizontal tests across the three different cylinder sizes. Note that the APRL hand was not able to grasp the smallest PVC cylinder in the horizontal test, and was therefore omitted in Fig. 5.

V. Human Subject Evaluation

In this section we will discuss the human subject study to test the functionality of the body-powered split hook, APRL hand and Yale Multigrasp Hand. The study was approved by the Yale Human Subjects Committee, Protocol Number 1411014968, and testing was done in accordance to the approved IRB practices and procedures [11].

A. *Able-Subject Testing*

The goal of our human subject testing was to compare the terminal devices by simulating ADL's common to its users. This testing was completed primarily by able-bodied participants with the use of a bypass socket (shown in Fig. 6), and by a smaller group of amputees with their current body-powered systems. The bypass socket is an arm brace with a distal adapter to simulate upper-limb prosthetic usage. The terminal device was actuated with a modular figure of nine harness that could be coupled to the bypass socket or an amputee's current prosthetic system. This body-powered harness was equipped with an embedded load cell for force measurements as well as a linear potentiometer to measure excursion. Sensor data was recorded during testing by a data logger that was strapped around the subject's waist.

Fig. 6. An instrumented bypass socket was used to evaluate the body-powered terminal devices with able-body subjects. Here, the subject is using the APRL voluntary-closing hand with a standard figure-of-nine harness.

To evaluate each terminal device, we requested that the participants undertake in several standardized performance tests and surveys. For each terminal device, participants completed a basic grasp test, box and blocks trials, and a SHAP assessment. In the basic grasp test, the user picked up and put down a random assortment of objects, that was consistent between participants and terminal devices, for ten minutes. This is not a standardized test and produced no results, however, this time was given as training for the participants to familiarize themselves with the given terminal device and to ensure they understood how to operate it. One of the two assessments used to evaluate the terminal devices is the Box and Blocks test [6]. In this test, participants move wooden cubes between two adjacent containers separated by a dividing wall. The goal of this test is to move as many one inch cube wooden blocks over the barrier in sixty seconds ensuring that the blocks are not thrown but placed in the adjacent container. The blocks are oriented randomly in the initial container which adds variability to each trial round. An image of one able-body subject performing the Box and Blocks test using the bypass socket can be seen in Fig. 7.

The second assessment was the SHAP test, which is a generic test of hand function consisting of 26 timed tasks [7]. These tasks are split between 12 abstract tasks and 14 ADL tasks, all of which are unilateral in nature and used to assess prehensile pattern use and performance. Scoring in the SHAP test is determined by how quick a user can start a timer, complete the task, and then stop the timer all with the terminal device. Times are recorded for each task. The scores ranges from 0 to 100 where 100 is human-like in speed and ability. A score is also assigned to each category of grasp types used throughout the test including spherical, tripod, power, lateral, tip, and extension. All of the tests were video recorded as a source of data redundancy, to ensure grasping trials were completed correctly, and to gauge user performance.

General questionnaires were another metric our group used to evaluate terminal device. These questionnaires included an entry survey to determine any potential bias in usage or performance before starting the testing. Post-terminal device surveys asked the participant general qualitative questions about how they liked the specific device and specific objects that they found easy or difficult to grasp. After the testing, an exit survey was administered that asked the participant to compare the devices and pick a device that they preferred during the testing.

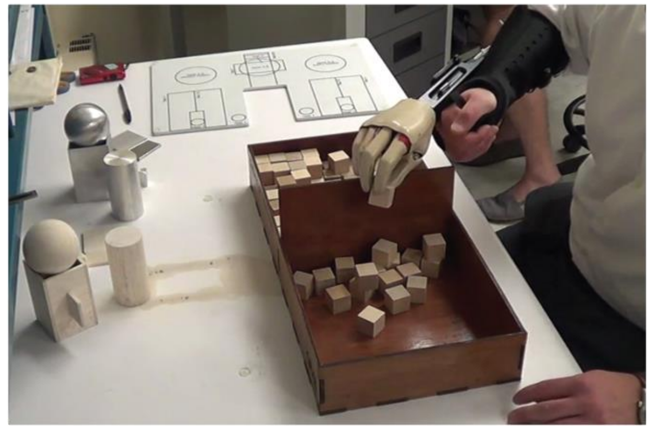


Fig. 7. An able-body subject performs the Box and Blocks test with the APRL and the by-pass socket.

1) Testing Protocol

In this study, there were a total of 12 able-bodied participants, 6 males and 6 females, all of which are right-hand dominant with no impairments, ages 18 to 36. Participants first filled out the entry questionnaire to identify potential bias. To test general user ability and to familiarize with the tests, we had each participant go through three rounds of the Box and Blocks and a full SHAP test with their dominant hand. For this dominant hand testing, we had no sensor data logging, bypass socket or prosthesis and would help the participant if they had any questions about rules and regulations in the specific tests or tasks. After completing a full test run and recording time data, the participants were fitted with the bypass socket, terminal device, and data logging equipment. Each participant would complete two full runs of testing with the Yale Multigrasp Hand and the Split-hook or the APRL hand chosen at random and in a random order. During the trials the first device would be labeled “Device A” and the second “Device B” to prevent possible naming bias for the Yale Hand. All terminal devices were used on the dominant right hand on which six participants used the APRL hand and six participants used the Split-hook. Before starting, the sensors were set-up and the load cell and linear potentiometer were calibrated. Next, the participant was introduced to a body powered system and taught the three main types of actuation: arm extension, opposite scapular protraction/retraction and shoulder abduction/adduction. The time would then start for the basic object test where the user explored the objects and workspace unguided for ten minutes. After a short break, the participants were introduced to the Box and Blocks test and were given 30 seconds to practice lifting the blocks over the barrier. The participants then did three 60 second trials of the Box and Blocks test with 30 seconds rest in between, and the number of blocks successfully placed over the barrier was recorded at the end of each trial.

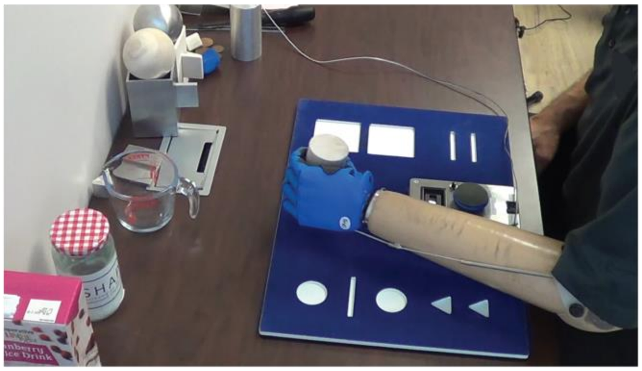


Fig. 8. An amputee subject uses the Yale Multigrasp Hand to complete the SHAP test. Here, the subject is manipulating the Heavy Cylinder abstract object.

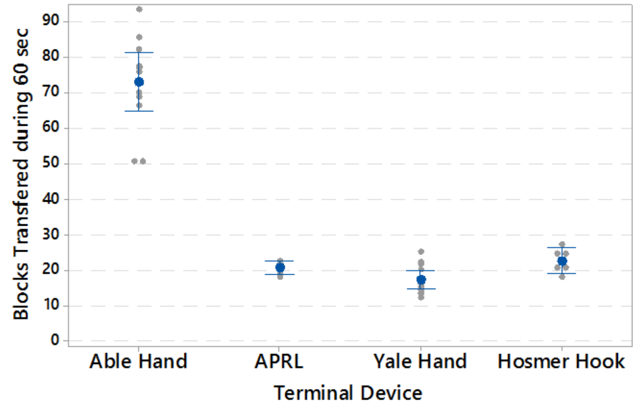


Fig. 9. Box and Blocks scores for able-hand and three different terminal devices performed by 12 able body subjects.

After the Box and Blocks test was completed, the participants started the SHAP test. The SHAP test is a standard test of upper extremity dexterity and is frequently used to evaluate upper limb prosthetic devices [7]. The participants were encouraged to practice as long as they wanted and then complete the task as quickly as possible. The amount of official trials was not limited, however, seldom went over three. During each task, the participants were asked if they wanted to try again or if they believed they could go faster. After completing the first terminal device, a post-device survey was completed to evaluate the hands performance as well as highlight tasks the participant found easy or difficult.

After a fifteen-minute break, the participants followed the same protocol for the second terminal device. After full completion of the three tests another post-device survey, which was identical to the first, was completed for that terminal device. The two devices were then taken off the bypass socket and placed next to each other for reference. The last step was the completion of the exit survey, which compared the two devices for certain tasks and in general appearance and then asked if the user would prefer one device over the other. All participants were compensated for their time of the testing, which lasted between three to four hours.

After the testing the scores would be logged and checked between the hand written results and the data logging software. The times for the SHAP test were entered to create an Index of Function (IoF) score, as well as providing a Functionality Profile (FP) score to the six prehensile pattern classifications – lateral, power, tripod, tip, extension, and spherical. The IoF and FP scores are determined based upon the completion of timed tasks which range from the grasp and movement of light and heavy abstract objects as well as ADL tasks. Normative data of healthy function yield an IoF and FP scores of 100±5 [7] where lower scores indicate impairment to the function of the hand under assessment. Completing all the tasks in the same time as the typical unimpaired user would result in a score of 100. Previous work on testing with able unimpaired subjects using their able hands on the SHAP test showed average scores between 96.7 and 99 [12]. The Box and Blocks scores were evaluated based on the number of blocks successfully transferred to the adjacent box, averaging around 20 blocks over the 60 second trial period when using the prosthetic terminal devices. Surveys were thoroughly reviewed and logged to determine user preferences and summarize the participants experience with each terminal device.

B. *Amputee Testing*

In this study we had the privilege of working with two amputee subjects, one was a unilateral amputee and one of which was a bilateral amputee. Both participants have been amputees for over ten years and have had extensive experience with body-powered systems. The unilateral amputee currently uses multi-grasp electric hands as his/her primary system, however, had a socket that could be fitted for a body-powered system. The bilateral amputee used body-powered split hook systems daily and preferred this over electrical systems. For these participants we adapted our data logging system to work with their socket and had the cable adjustments and fitting done by a trained prosthetist. The testing protocol was completed in the same way as the able-bodied users in the amputee testing, minus the initial able-bodied test run.

VI. Human Subject Testing Results

A. *Box and Blocks Test*

The Box and Blocks test proved to be a simple evaluation of a very repetitive task. Although the results did not show the versatility of any of the terminal devices, it did reflect the ability of quick actuation provided by the body-powered terminal devices. Fig. 9, shows the results of the Box and Blocks test for the three different terminal devices tested. The average number of blocks transferred by the subject's able hands was 73.1 with a range of 50 to 93 blocks in 60 seconds. Although the number of blocks transferred with the Yale Hand (17.3) was on average lower than the Hosmer Hook (22.7) or APRL Hand (20.7), there was no statistical significance between the averages of the three terminal devices on the Box and Blocks test based a paired t-test of means.

The two amputees who conducted the trial scored a 45.6 and a 29.3 average with the Hosmer Hook. These scores are much higher than the able-body subjects because both amputee subjects had previous experience using this terminal device. Their scores for the Yale Multigrasp hand were 9.6 and 13. Both subjects reported the lack of experience with this terminal device as the reason for the lower scores on the Box and Blocks test.

B. SHAP Test Scores

The twelve able-bodied subjects performed the SHAP test first with their able hand to better understand the protocol and to establish a baseline in performance. Fig. 10 shows the SHAP scores for the able hand (101.2) were within the range specified by the expended variance in repeated tests of the SHAP test and indicates unimpaired hand function as expected.

For testing of the terminal devices with able-bodied subjects, the APRL hand had an average overall SHAP IoF of 65 while the Yale Multigrasp Hand had an overall IoF of 64.1. The Hosmer Hook scored a 64.8 overall. Fig. 10 show a direct comparison of all subjects with the three different terminal devices over the full breakdown of grasp types.

Although statistically speaking, the three terminal devices performed very similarly (P value in paired T-Test = 0.81-0.86), the Yale Multigrasp Hand performed better on the spherical and power grasps while performing worse in the tip grasp. The two amputee subjects had an overall SHAP score of 36 and 40 with the Yale Hand, and 50 and 81 with the Hosmer Hook.

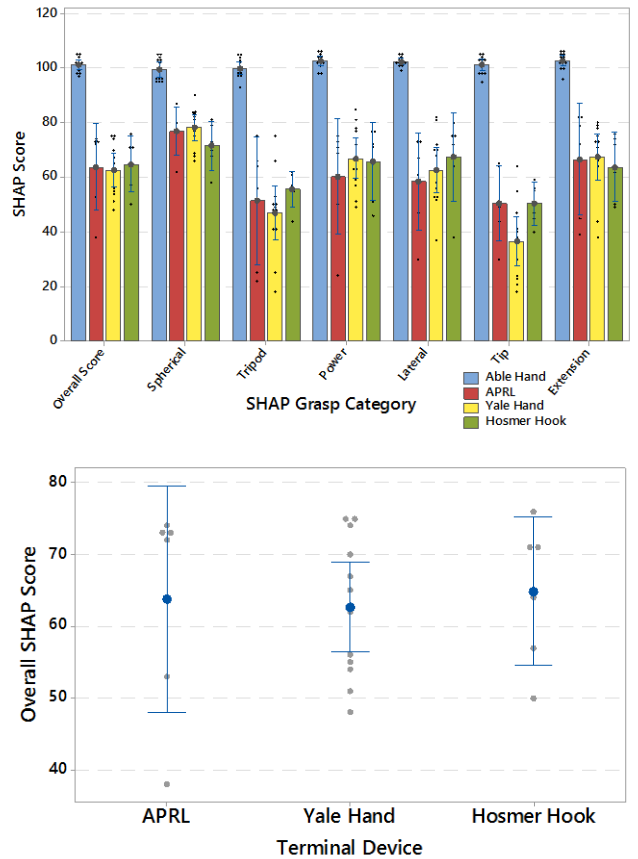


Fig. 10. Score comparison between the terminal devices and the resulting SHAP scores.

VII. Discussion

A. Test Score Comparison

Terminal devices in the professional prosthesis market that have released SHAP scores are the iLimb Pulse by Touch Bionics, the Ottobock Michelangelo Hand and the Hosmer Hook. The iLimb Pulse by Touch Bionics is a five actuator and six degree of freedom electrically powered hand driven by worm gears paired to DC motors. The iLimb Pulse scored an 88 on the SHAP test performing very high on spherical grasps and low on tip grasp [13]. The Michelangelo hand by Ottobock is a two actuator and two degree of freedom electrically powered hand driven by an internal cam mechanism paired to DC motors. The Michelangelo hand scored a 59 on the SHAP test performing very well in spherical and weak on tip grasp [14]. Like most electrically actuated hands, the Michelango was able to complete most of the tasks but fell short due to the input delay in most myoelectric grasping systems. The body powered, voluntary-opening Hosmer Hook scored a 66 on the SHAP test, which is a great performance for a single degree of freedom system [14]. The Hosmer Hook scored favorably due to the quick opening and closing capabilities of body powered systems and the extensive grasp range that allows for grasping of objects with a wide variety of sizes. All of the scores referenced here for commercial terminal devices were evaluated using amputee participants.

Research terminal devices that have released SHAP scores are the Vanderbilt Hand and the RIC VO/VC hand. The Vanderbilt Hand is a five actuator and six degree of freedom electrically powered hand driven by brushed DC servomotors. The Vanderbilt Hand scored an 87 on the SHAP test for able-bodied participants using a bypass socket. The terminal device performed very well on the tip grasp, however, performed weak on the power grasps [15]. The RIC VO/VC hand is a body powered split hook with a flip switch that allows the device to change between voluntary opening and voluntary closing. The RIC hand scored 53 on the SHAP with amputee participants and 58 on the SHAP with able-bodied participants [16]. Although the SHAP test does not require sustained grasping tasks, the force variability from voluntary closing prosthesis paired with the sustained force from voluntary opening prosthesis is a unique approach of addressing the tradeoffs that occur in most body-powered systems that are either voluntary-opening or voluntary-closing.

B. Conclusion

Evaluation of the function of prosthetic terminal devices is difficult to perform without inherently measuring the capabilities of the user. Although the tests were conducted across a wide range of subjects, we saw similar scores in the SHAP test for all three terminal devices. The scores varied greatly as compared to the scores of the amputee subjects who had numerous years of practice and real world experience with the devices such as the Split-hook.

In the questionnaires, subjects stated that they preferred the weight and appearance of the Yale hand to the APRL Hand. Although users did prefer the voluntary opening behavior of the split-hook, they stated that they had a higher difficulty regulating how hard they were grasping. This could be difficult when it comes to consecutive grasps of objects with varying weights and stiffness, however, could be advantageous when it comes to sustaining grasps over a long period of time.

In the future, we would like to test our hand with more unilateral and bilateral amputee subjects. Although we did find large benefit to having multiple grasp types, the manual switching between grasps needs to be improved to make the system more intuitive for new users. We would also like to continue additional testing where the subjects are exposed to more than two terminal devices. Since almost all subject expressed that they felt they were getting better at using the device toward the end of the test, we could also incorporate longer term testing to understand the learning effect better with various hand designs.

Overall, the Yale Multigrasp hand proved to be as effective as commercially available terminal devices to those who had not had any previous experience using the devices. The amputee subjects, although scoring lower on all tests with the Yale Multigrasp Hand over the Split hook, stated that they thought the multiple grasp types were useful in performing a variety of tasks. The amputee subjects also stated that they believed they would be able to improve their scores with additional practice using the Yale Multigrasp hand.

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References

[1] H. Lui, K. Wu, P. peusel N. Seitz G, Hirzinger, M.H. Jin, Y.W. Lui, S. W. Fan, T. Lan, Z.P. Che, "Multisensory five-fingered Dexterous Hand: The DLR:HIT Hand II,", *Proceedings of the 2008 IEEE/RSJ Intern. Cont. on Intelligent Robotic systems,* pp. 3692-3697, 2008.

[2] C. Cipriani, M. Controzzi, M.C. Carrozza, "Objectives, criteria and method for the design of the smarthand transradial prosthesis, *Robotica*, Vol. 28, pp 919-927, 2010.

[3] S. A. Dalley, T. E. Wiste, T. J. Withrow. M. Goldfarb. "Design of a Multifunction aln anthropomorphic Prosthetic hand with extrinsic actuation" *IEEE/ASME transations on mechantronics*, 2009.

[4] J. T. Belter, J. L. Segil, A. M. Dollar, R. F. Weir, "Mechanical deisgn and performance specification of anthropomorphic prosthetic hands: A reviw" *Journal of Rehabilitation Research and Development*, Vol. 50. No. 5, 2013.

[5] J. W. Sensinger, J. Lipsey, A. Thomas, and K. Turner. "Design and Evaluation of Voluntary Opening and Voluntary Closing Prosthetic Terminal Device." *Journal of Rehabilitation Research & Development*, Vol. 52. No. 1, 2015.

[5] CM Fryer, JW Michael. Upper-Limb Prosthetics: Body-Powered Components. *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles. American Academy of Orthopedic Surgeons*; 1992.

[6] G. Volland, N. Kashman, K. Weber, "Adult Norms for the Box and Blocks Test of Manual Dexterity" *The Americal Journal of Occupational Therapy*, Vol. 39, No. 6, 1985.

[7] SHAP Test Protocol and Proceedure (http://www.shap.ecs.soton.ac.uk).

[8] Hosmer Prosthetics and Orthotics, Hosmer Terminal Device Product Catalog, 2011. (www.hosmer.com/products).

[9] G. Smit, "Natural Grasping, design and evaluation of a voluntary closing adaptive hand prosthesis", *University of Delft, thesis*, 2013.

[10] NIST Grasp Standard Tests available (http://www.nist.gov/el/isd/grasp.cfm).

[11] Yale Human Subjects Committee. Novel Body-Powered Prosthetic Hand Evaluation and Comparison. 2014;Protocol Number 1411014968

[12] Norling Hermansson, Liselotte M., Andrén, Martin, Johansson, David. Swedish normative data for the Southampton Hand Assessment Procedure – SHAP. 2014.

[13] Niet, Olga Van Der, Raoul M. Bongers, and Corry K. Van Der Sluis. "Functionality of I-LIMB and I-LIMB Pulse Hands: Case Report." *Journal of Rehabilitation Research and Development*, Vol. 50, No. 8, pp. 1123-1128, 2013..

[14] P. J. Kyberd, A. Murgia, M. Gasson, T. Tjerks, C. Metcalf, P. H. Chappell, K. Warwick, S. E. M. Lawson, and T. Barnhill, "Case studies to demonstrate the range of applications of the southampton hand assessment procedure," *The British Journal of Occupational Therapy*, Vol. 72, No. 5, pp. 212-218, 2009.

[15] S. A. Dalley, D. A. Bennett, and M. Goldfarb, "Preliminary functional assessment of a multigrasp myoelectric prosthesis," *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4172-4175, 2012.

[16] Sensinger, Jon, Jim Lipsey, Ashley Thomas, and Kristi Turner. "Initial Experience with the RIC VO/VC Terminal Device." *Myoelectric Controls Symposium Proceedings*, pp. 220-222, 2014.