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Article

The effects of vibrotactile feedback on task performance in a 3D-printed myoelectric prosthetic arm

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SUMMARY

The lack of tactile feedback in today's hand prosthetics complicates the user experience by forcing a user to visually confirm that the prosthetic is grasping an object. This study strives to remedy both the financial and mechanical deficiencies in current prosthetics through building a simple, noninvasive, vibratory sensory feedback system into an inexpensive constructed 3D-printed prosthetic arm. This 3D-printed prosthetic arm was designed in SolidWorks and printed to the specifications of a participant with a left forearm amputation. The myoelectrical components include a muscle sensor that sends electrical signals to an Arduino microcontroller, which translates the data into code orders to trigger a servo motor to open or close the hand. Vibrotactile feedback was implemented by using a touch sensor on the tip of the index finger of the prosthetic that activates a vibrating motor attached to the residual arm. To test the efficacy of the sensory feedback, the participant was asked to perform a series of tasks both with and without the vibrotactile feedback, both blindfolded and non-blindfolded. The presence of vibrotactile feedback was essential for completing blindfolded tasks, but it did not assist in improving non-blindfolded task performance. The total cost of materials to build this prosthetic arm was $158.46. This study supports the hypothesis that the simple sensory vibrotactile feedback system in the design of this 3D-printed myoelectric prosthetic arm has the potential to enhance sensory feedback performance of amputees by decreasing visual dependency, at a fraction of the cost of a custom-designed myoelectric prosthetic.

INTRODUCTION

According to the nonprofit Amputee Coalition, of the two million amputees living in the United States, 350,000 suffer from upper limb loss (1). While a single prosthetic that achieves both a natural appearance and extreme functionality would be ideal, most artificial limbs that exist today sacrifice one for the other in varying degrees.

The major prosthetic categories for upper limbs include cosmetic, body-powered, and myoelectric prosthetics. Cosmetic prosthetics have little to no functional use and are made primarily of silicone to resemble the user's original limb appearance (2). The lack of mechanical functionality yields a relatively lightweight prosthetic, as the mechanical components are not required. In terms of cost, they are the most affordable prosthetics.

Body-powered prosthetics rely on a system of cables or harnesses to control the prosthetic limb by moving other parts of the body, such as the shoulder girdle, elbow, and chest. Moving the body parts in a certain way will pull on the cable and cause the prosthetic hand to open or close (3). While they are highly durable, the body-powered prosthetic requires unnatural movements of the connected body parts, which can make movements awkward for the user (4). Over time, the prosthetic straps and cables can become uncomfortable and difficult to operate and will need ongoing adjustments and repairs (5).

Externally powered artificial limbs such as myoelectric prosthetics are an attempt to solve the physical exertion issue by using a battery and an electronic system to control movement. Myoelectric prosthetics, unlike body-powered prosthetics, do not require any straps or harnesses to function, thus providing a more natural appearance. They are custom made to fit the remaining limb. The prosthetic's movement is initiated by muscle contractions on the residual limb, which alter resistance in muscle detector sensors. This information is relayed to a microprocessor, which deciphers the readings and instructs a servo motor to turn and adjust the position of the fingers to open and close the hand (6). Currently, the main disadvantages of myoelectric prosthetics are their weight and cost (7). Myoelectric prosthetics tend to be heavier because of the required hardware for operation. While they are more expensive than other kinds of prosthetics, they offer the best quality regarding both cosmetics and functionality.

Rudimentary myoelectric prosthetics close the entire prosthetic hand when a single muscle contraction is detected, which greatly increases its initial ease of use. Advanced myoelectric prosthetics use multiple sensors and motors activated by different muscle contractions on the residual limb to allow for control of individual fingers. Extensive training and knowledge are necessary for the user to effectively use this type of prosthetic (8).

The functionality of a prosthetic plays a vital role in the selection process, as does the cost. On average, a cosmetic prosthetic costs between 3,000 to 5,000 USD; a body-powered prosthetic costs around 10,000 USD; and a commercial myoelectric prosthetic can range in cost from 20,000 to 100,000 USD (9). Commercial 3D-printed myoelectric prosthetics, such as the Dexterous Hand by Shadow Robot Company and the Hero Arm by Open Bionics, are considered the more affordable myoelectric alternatives, with prices as low as 2,500 and 6,500 USD, respectively (10, 11). The reduced cost of these 3D-printed prosthetics has proven especially beneficial for children, as with continued growth and use, children frequently require prosthetics to be repaired, replaced, and re-fitted. We decided to use 3D printing to manufacture the device in this study primarily due to its affordability.

Upper limb prosthetics remain limited in complex motor and sensory feedback despite the advancements in prosthetic technology and cost associated with prosthetics. Sensory feedback is critical in restoring functionality to amputees, as it would relieve the cognitive burden of relying solely on visual input to monitor motor commands. Already in use is a technique called sensory substitution in which one type of sensation is substituted for another. For example, vibration applied to the skin of the remaining limb, or to another part of the body, is used to convey touch from sensors on the prosthetic. Vibrotactile stimulation through sensory substitution was the sensory feedback system of choice incorporated in this research as it is inexpensive, noninvasive, and could be easily implemented into myoelectric prosthetic technology (12).

Other methods of feedback include various types of implanted neural interfaces—electrodes implanted in the proximity of the residual nerves of the amputated arm—which are activated by sensors on the prosthetic. This direct neural stimulation approach shows promise for enabling patients to detect object characteristics including size, shape, and stiffness to control fine motor movements without visual cues (13). Current approaches in testing seek to avoid implanted nerve electrodes by using a technique called sensory regenerative peripheral nerve interface (sRPNI), in which a "bioartificial interface" transfers sensory signals directly from a prosthetic sensor to the remaining nerve (14). However, despite their promise, we were not able to explore these new technologies in this study due to limited funds.

The purpose of this study is to determine the efficacy of a vibratory tactile feedback system placed on the index finger of an inexpensive constructed 3D-printed myoelectric prosthetic arm in performing various tasks. We were able to construct the prosthetic with a total materials cost of $158.46. We evaluated the efficacy of the vibrotactile feedback by having a participant with a left forearm amputation wear the constructed 3D-printed myoelectric prosthetic arm while performing functional tests, non-blindfolded and blindfolded, with and without vibrotactile feedback. The presence of vibrotactile feedback proved essential for completing blindfolded tasks. However, vibrotactile stimulation did not improve task performance when the participant had the aid of vision. At a fraction of the cost of a custom-designed myoelectric arm, the design of this 3D-printed myoelectric prosthetic arm has the potential to enhance sensory feedback performance for the amputee using a simple sensory vibrotactile feedback system.

RESULTS

Construction of the 3D-Printed Myoelectric Prosthetic Arm

This 3D-printed myoelectric prosthetic arm was designed to the specifications of a participant with a left forearm amputation. The prosthetic was then designed in a 3D modeling software, Solidworks. The phalanges of the fingers went through five prototypes before the final design. Once the CAD designs were completed, the models were 3D printed using ABS plastic. The prosthetic utilized an Arduino microcontroller in tandem with a servo and a MyoWare muscle sensor to control the grasping motion. An additional feedback system was integrated into the index finger which gave the user feedback by way of a vibrating motor **(Figure 1a-d)**.

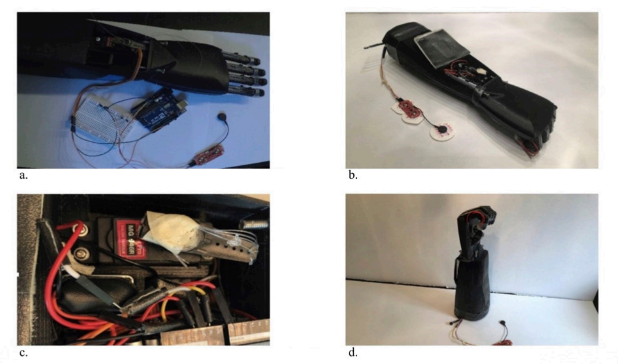

Figure 1: Images of completed 3D printed myoelectric prosthetic. (a) electronic components before assemble, (b) electronic components housed in forearm, (c) close up of electronics housing, (d) complete 3D printed prosthetic arm.

Task Performance Testing

Testing was conducted by asking the participant to complete a series of tasks while blindfolded and non-blindfolded **(Figure 2a-f)**. To evaluate the efficacy of the vibrotactile feedback system, each task was performed 5 times under consistent conditions with and without the vibrotactile feedback. The average of the 5 values was taken as the final performance metric for each task. Failure to complete a task is defined as taking longer than 60 seconds. The paired sample t-test in Microsoft Excel was used to compare the statistical difference between the time taken to perform the tasks with the presence and absence of vibrotactile feedback while blindfolded and non-blindfolded.

Blindfolded Tasks

Vibrotactile feedback efficiency was evaluated by observing the participant's completion of three simple tasks while blindfolded. The absence of the vibrotactile feedback resulted in significant failure to complete all three tasks (p<0.001) while blindfolded. The participant failed to detect the presence of the block on her palm, locate the block on the tray, or determine if her prosthetic was being touched. With vibrotactile feedback activated, the participant successfully completed all three tasks **(Table 1a, 1b)**.

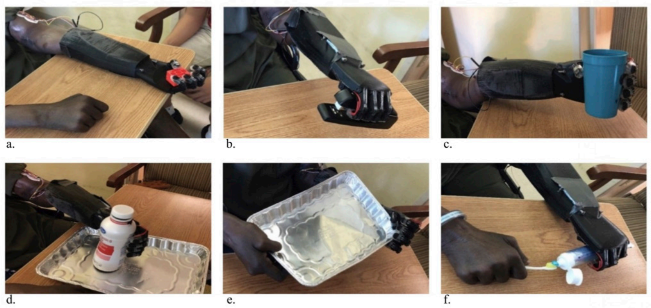

Figure 2: 3D printed myoelectric prosthetic arm conducting various non-blindfolded tasks. (a) Pick up a light object/plastic cube, (b) pick up a heavy object/ sampler, (c) hold a cup, (d) pick up bottle and transfer to tray, (e) pick up travy, (f) squeeze a toothpaste onto toothbrush.

Blindfolded Tasks		Trials (seconds)					
Trial Number		1	2	3	4	5	Average
With VF	Detect if index finger with tactile sensor was touched	2	1	1	2	1	1.4
	Detect block on palm with fingers closed	15	16	13	10	8	12.4
	Locate block on tray	27	25	30	24	34	25.8
Without VF	Detect if index finger with tactile sensor was touched	F	F	F	F	F	F
	Detect block on palm with fingers closed	F	F	F	F	F	F
	Locate block on tray	F	F	F	F	F	F

Table 1a: Blindfolded tasks performed with and without vibrotactile feedback over 5 trials.

Blindfolded Tasks	Without VF Mean time (s)	With VF Mean Time (s)	p-value
Detect if index finger with tactile sensor was touched	F	1.4	<0.001
Detect block on palm with fingers closed	F	12.4	<0.001
Locate block on tray	F	25.8	<0.001

Table 1b: Comparison of blinded tasks performed with and without vibrotactile feedback. Failure= F(Is defined as 60 seconds or more)

Non-blindfolded Tasks

There was no statistical significance in efficiency of task performance observed with vibrotactile feedback or without vibrotactile feedback in the absence of a blindfold ($p > 0.05$). In either case, the participant was able to successfully pick up a light plastic cube (20 g) and a heavy stapler (500 g), to hold a cup, pick up a bottle and transfer it onto a tray, to hold a tray, and to squeeze toothpaste onto a toothbrush. Fine motor task completion, such as picking up a coin and cutting food, was an overall failure regardless of whether the vibrotactile feedback was present **(Table 2a, 2b).**

Cost of Constructing the 3D-Printed Myoelectric Prosthetic Arm

The total cost of all the materials required to construct this 3D-printed myoelectric prosthetic arm, all of which could be purchased on Amazon, was $158.46 **(Table 3)**.

Unblindfolded Tasks		Trials (seconds)					
Trial Number		1	2	3	4	5	Average
With VF	Pick up a coin	F	F	F	F	F	F
	Cutting food	F	F	F	F	F	F
	Pick up a light object (plastic cube = 20 g)	40	38	36	41	35	38.0
	Pick up a heavy object (stapler = 500 g)	12	15	14	12	13	13.2
	Hold a cup	10	11	12	8	14	11.0
	Pick up a bottle and transfer it onto a tray	52	47	43	45	48	47.0
	Hold a tray	15	16	19	20	13	16.6
	Squeeze toothpaste onto toothbrush	55	60	50	46	48	51.8
Without VF	Pick up a coin	F	F	F	F	F	F
	Cutting food	F	F	F	F	F	F
	Pick up a light object (plastic cube = 20 g)	42	45	38	39	37	40.2
	Pick up a heavy object (stapler = 500 g)	11	13	15	19	12	14.0
	Hold a cup	8	9	12	11	13	10.6
	Pick up a bottle and transfer it onto a tray	53	50	47	45	48	48.6
	Hold a tray	13	14	17	14	16	14.8
	Squeeze toothpaste onto toothbrush	51	53	49	48	43	48.8

Table 2a: Non-blindfolded tasks performed with and without vibrotactile feedback over 5 trials.

Unblindfolded Tasks	Without VF Mean Time (s)	With VF Mean Time (s)	p-value
Pick up a coin	Failure	Failure	N/A
Cutting food	Failure	Failure	N/A
Pick up a light object (plastic cube = 20 g) **(Figure 1a)**	40.2	38.0	0.09
Pick up a heavy object (stapler = 500 g) **(Figure 1b)**	14.0	13.2	0.2
Hold a cup **(Figure 1c)**	10.6	11.0	0.1
Pick up a bottle and transfer it onto a tray **(Figure 1d)**	48.6	47.0	0.05
Hold a tray **(Figure 1e)**	14.8	16.6	0.1
Squeeze toothpaste onto toothbrush **(Figure 1f)**	48.8	51.8	0.06

Table 2b: Comparison of non-blindfolded tasks performed with and without vibrotactile feedback.

Materials	Cost
HATCHBOX 1.75mm White PLA 3D Printer Filament - 1kg Spool - Dimensional Accuracy +/- 0.05mm	$19.99
MyoWare Muscle Sensor	$37.99
Elegoo EL-KIT-004 UNO Project Basic Starter Kit with Tutorial and UNO R3 for Arduino	$17.65
5pcs DC3V/0.1A 1.5V/0.05A 10x2.7mm Coin Mobile Phone Vibration Motor	$5.28
Energizer Max Alkaline 9 Volt, 4-Count	$10.38
RioRand MG946R High Torque Servo for Motor Helicopter Boat Model.	$9.90
3M Red Dot Foam Monitoring Electrode, 4.4 cm Diam., 50/Bag, 3M9640	$12.84
Orthodontic bands	$5.50
Energizer Max Alkaline AAA, 4-Count	$3.74
10 Pieces Black Latching self locking 1A push button on off micro mini 1208YD B5	$10.00
10-32 x 1" Button Head Socket Cap Screws, Allen Socket Drive, Stainless Steel 18-8, Full Thread, Bright Finish, Machine Thread, Quantity 50 By Fastenere	$12.20
Striveday™ 30 AWG Flexible Silicone Wire Electric wire 30 gauge Coper Hook Up Wire 300V Cables electronic stranded wire cable electrics DIY BOX-1	$12.99
Total cost	**$158.46**

Table 3: Breakup cost of materials used for constructing the 3D-printed myoelectric prosthetic arm with vibrotactile feedback.

DISCUSSION

New technological advancements in the field of myoelectric prosthetics have led to the development of hands with multiple degrees of freedom of movements. Unfortunately, current upper limb prosthetics are still limited in terms of complex motor control and sensory feedback. The lack of sensation is the key limitation to reestablishing the full functionality of the natural limb. Providing some sense of touch to the artificial hand would lessen the cognitive burden of relying solely on vision to initiate and monitor movements.
Sensory substitution, the vibrotactile feedback modality used in this myoelectric prosthetic arm, is simple, inexpensive and noninvasive but has major limitations. During ordinary wear over time, sweat can impede the connection between the

electrode and the skin, so that the user feels less or even no feedback at all. This limitation was exhibited during testing, which necessitated changes of electrode pads to enhance better adherence to the skin. Additionally, in this iteration, the vibrotactile feedback was present only on the index finger of the prosthetic. This could be improved by having touch sensors in multiple areas, such as the palm and fingers.

The participant failed to complete two fine motor tasks, including cutting food and picking up a coin, with or without the presence of vibrotactile feedback. The failure to cut food can be attributed to the lack of wrist articulation. Because of the absence of a wrist joint in the design of this prosthetic, the participant is relegated to performing tasks in which the object can be grasped or held perpendicular to the forearm. Though this orientation can be rotated to hold objects vertically or horizontally, which encompasses many daily activities, the inability to properly hold a knife reveals a more overarching limitation. The participant was able to complete the remaining tasks regardless of the locked wrist.

The participant's inability to pick up a coin is caused by the deliberate design of the fingers. Because of the design of the control system, in which the muscle sensor activation results in the simultaneous closing of the hand, the hand would excel at picking up larger everyday objects rather than manipulating much smaller objects with individual fingers. Knowing this beforehand, the fingers were designed with large rubber tips to further strengthen the prosthetic's ability to pick up larger objects.

The prosthetic excelled particularly at picking up cylindrical objects such as a bottle or a cup. This ability can be attributed to the curved surface of the palm, which was designed to emulate the curved nature of a clenched hand. The prosthetic continues to retain the ability to grasp angular objects due to its relatively gradual curve.

Throughout the testing, once the participant was able to grasp an object, the participant would not involuntarily lose control of the object. The participant used a toggle system, where a muscle contraction detected by the muscle sensor on the residual limb would cause the hand to close and another would cause a release. Prior to the addition of the toggle control, in personal testing, the participant found difficulty in retaining an object in the prosthetic's grip once picked up, as it required constant muscle contraction to remain in the closed state.

The participant did not report unintentional activations post calibration. Previous versions that excluded an average of the sensor values resulted in sporadic control and unintentional activations. These unintentional activations were caused by the sensor over exaggerating abrupt minute changes in sensor values while the participant was resting her muscle.

Some more complex prosthetics use multiple sensors positioned at muscles along the residual limb to detect multiple different signals and allow the user to individually actuate each finger, resulting in a more accurate emulation of a human hand. This prosthetic used a single muscle sensor to detect a single muscle contraction to simultaneously close all the fingers of the hand. The simplicity of a single muscle stimulation may prove beneficial in reducing the time required to master the use of a prosthetic in comparison with more advanced options. Though a single sensor reduces the learning curve, the simultaneous closing of all five fingers is a notable limitation since each finger cannot be individually controlled. Future iterations could use five separate muscle sensors and five servos to allow for independent movement for each finger. This will, however, not only increase the weight but the overall cost in producing the prosthetic.

This study utilized only one participant who performed each task five times to determine the efficacy of the vibrotactile feedback of the 3D-printed myoelectric prosthetic arm. While relegating the various performance tasks to only a single participant ensured the data between activated and deactivated vibrotactile feedback would be comparable, the small sample size decreased statistical power and inflated false discovery rate. Future iterations could utilize multiple participants as this would provide data on how the prosthetic performs on different people and can expose shortcomings that are not immediately evident on the participant in this study.

Testing other available prosthetics could provide data on the effectiveness of this prosthetic relative to its prospective competitors. This prototype aims to replicate the function of more costly commercial myoelectric prosthetics. A participant performing identical tasks using this prosthetic as well as other different myoelectric prosthetics could compare the shortcomings and advantages of each option. Comparable testing using other commercial prosthetics was not done in this study because of cost restrictions.

This study found that the presence of vibrotactile feedback proved to aid the participant only in situations with complete absence of vision. Future testing could assess the effectiveness of the vibrotactile feedback in different environments with varying degrees of brightness. Replicating the same tests in varying lower visibility settings would demonstrate the effects of different levels of darkness has on the user and vibrotactile feedback's ability to change the user's performance. Another way to test the user's performance in a reduced visibility environment would be controlling the prosthetic with decreased peripheral vision. The user could attempt to complete the tasks while looking straight ahead and performing each task on the edge of their peripheral vision or at the corner of their eyes.

All the materials required to construct this 3D-printed myoelectric prosthetic arm were purchased on Amazon for $158.46 **(Table 5)**. Commercial myoelectric prosthetics can cost around $20,000 to $100,000. The more affordable commercial 3D-printed myoelectric prosthetic arms can range between $2,500 to $6,500. While many patients cannot afford the most cutting-edge technology, demand for prosthetic-and promising techniques from the 3D-printing industry may make them more affordable.

The absence of the vibrotactile feedback resulted in significant failure to complete all three tasks while blindfolded; the participant was able to successfully complete the three blindfolded tasks with vibrotactile feedback activated ($p<0.001$). There was no significant statistical increase in efficiency of task performance observed with or without vibrotactile feedback in the absence of a blindfold ($p>0.05$). This study provides evidence that vibrotactile feedback enhances the user's performance in situations in the absence of vision. This inexpensive 3D-printed myoelectric prosthetic arm has the potential to enhance sensory feedback performance of amputees and provide a substitution to the amputated limb, at a fraction of the cost of a custom-designed commercial myoelectric prosthetic.

MATERIALS AND METHODS

Construction of a 3D-Printed Myoelectric Prosthetic Arm with Vibrotactile Feedback for a Participant with Left Forearm Amputation

Measurements of the Participant's Limb

Participant: A left forearm amputee participated in the study. An Institutional Review Board (IRB) at The Westminster School approved the experimental protocol. Informed consent was obtained from the subject.

The process of designing this 3D-printed myoelectric prosthetic arm began with measuring the participant's left amputated forearm residual limb. The intact right arm was also measured for comparison.

Computer Assisted Drafting (CAD)

The original 3D-printed prosthetic arm designed for the participant with a left forearm amputation was created using a computer aided drafting (CAD) software called SolidWorks by drawing 2D sketches and extruding those sketches into 3D objects.

Fingers: Fourteen individual phalanges were created. The thumb had 2 phalanges, while each of the remaining four fingers had proximal, middle, and distal phalanges. All followed the same design concept in which an original 0.6 by 0.6 square was extruded to the desired length of each phalange. To create the curved appearance, symmetric fillets on the remaining edges of the prism were added. The phalanges of each finger were linked by a series of joints and pins. A small hole ran through each phalange that corresponded to the next so that the fishing line that acted as a "tendon" could be threaded through the phalanges to form the fingers **(Figure 3a, 3b).**

Optimal functionality of the prosthetic fingers was achieved through the trial and error of five phalange prototypes. In the first iteration, joint fulcrum placement was initially below an overhanging cosmetic cover, which resulted in the fishing line "tendon" placement above the joint. Subsequently, flexing the fingers would rely solely on orthodontic bands. Using the force provided by orthodontic bands to grasp ultimately wasted the servo's power by relegating it to opening the hand and overcoming the minimal force provided by orthodontic bands. The first iteration's **(Figure 4; V1)** reliance on orthodontic bands to close the hand and its omission of mounts for the bands made the fingers non-functional.

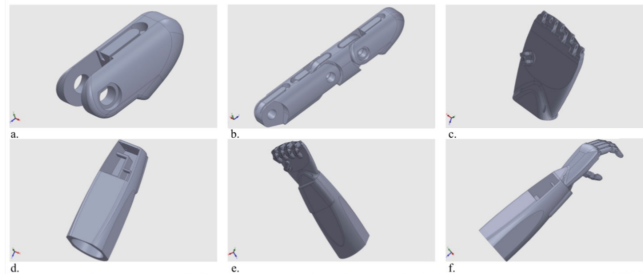

Figure 3: 3D models of various 3D prosthetic components: (a) distal phalange, (b) assembled proximal and distal phalanges, (c) palm, (d) forearm, (e) palmer aspect of assembly, (f) dorsal aspect of assembly.

The second iteration **(Figure 4; V2)** repositioned the joint fulcrum, which allowed the orthodontic bands to open the hand and used the servo's power to flex the fingers to close the hand. However, this prototype lacked orthodontic band mounts.

The third prototype **(Figure 4; V3)** introduced the first iteration with orthodontic band mounts, which involved creating channels on the top of each phalange. This iteration was the first fully functioning prototype that used the servo's power to flex the fingers and orthodontic bands to extend the fingers to open the hand. The channels, however, were large relative to future iterations. The large channels allowed the bands to pop out easily; therefore, "caps" were introduced. The caps proved problematic, as they were bulky, and friction fitted with minimal tolerance between the cap and the phalange; hence, it required a vice for installation. The "caps" were difficult to work with, because they tended to snap during removal and installation. When they did not snap, the necessity for a vice and pliers was tedious and complicated the process. These factors led to the creation of Version Four.

The fourth iteration **(Figure 4; V4)** reduced the width at the top of the channel and widened the gap towards the bottom. This design trapped and secured the orthodontic bands once they were installed. The reduced gap size increased the difficulty of mounting the orthodontic bands into the channel but held them without the need for "caps."

The final prototype, **(Figure 3a, 5)** utilized the same tapered channel design of the previous iteration, with a larger gap at the front of the channel to allow for easier insertion of orthodontic bands. The increased tolerance between the joint and pin eliminates the need for sanding.

Palm: The palm was dimensioned to the size of the participant's existing right palm. The design for the palm was based around spacing the fingers 1.6 cm. apart while keeping the overall width 9 cm. and the length 10 cm. While each finger was identical in length, the palm's mounting joints were staggered, leaving each finger at a different level in order to emulate a real hand. Keeping the finger lengths the same, shortens the design of time of having to design 5 fingers of various lengths. At the bottom of the palm, a slight curve was implemented to more closely resemble the closed hand and allow for more effective grasping. The five fishing lines for the five fingers were threaded through the five tunnels inside the palm, threaded through the forearm, and grouped together to attach to the servo arm. Four tap size 10-32 holes were made on the back of the palm to bolt it to the forearm **(Figure 3c)**.

Forearm: The forearm consisted of two major compartments: a sleeve to accommodate for the participant's amputated forearm/stump and the electronics-housing compartment. Additional paddings were inserted between the prosthetic arm sleeve and the participant's arm to ensure the device stayed on the residual limb and provide comfort for the user. The electronics-housing compartment was further subdivided into two separate spaces to secure the 5-volt servo and the 9-volt battery. The remaining space housed the Arduino, AAA battery, and electrical wiring (**Figure 3d, 3e, 3f**).

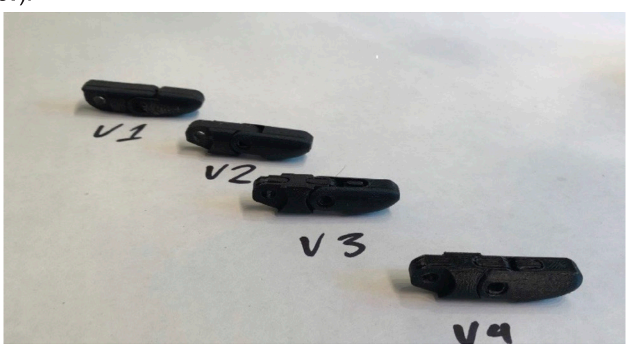

Figure 4: 3D-printed versions (V) of the distal and middle phalanges V1 to V4.

3D-Printing

Acrylonitrile butadiene styrene (ABS) filament was used for the printing of this prosthetic arm. It requires a heated bed to prevent the outer layers from curling in or wrapping, which guarantees an even distribution of heat to both inner and outer layers (15). By nature, ABS plastic also shrinks following a print or injection mold. Therefore, the prosthetic's size was over-exaggerated in the g-code to compensate for the 8.5% shrinkage. The 3D-printed components of the prosthetic hand—the palm and the proximal, middle, and distal phalanges—are shown in **(Figure 5)**. The 3D-printing data of this prosthetic arm is represented in **(Table 1).**

MyoWare Muscle Sensor

The MyoWare Muscle Sensor was applied to the skin directly on top of the muscle of the residual limb. It uses electromyography (EMG) to measure the electrical activity of the muscle contraction and converted the data into varying voltages that could be understood by electronic devices such as Arduino microcontrollers. The connections and the electrical circuitry between the MyoWare Muscle Sensor, Arduino, servo, and 9-Volt battery are shown in **(Figure 6,**

Figure 5: Unassembled 3D- printed components palm proximal, middle, and distal phalanges.

Part Name	Print Time (Minutes)	Infill Percentage	Layer Height
Distal Phalange V1	69	50	3
Distal Phalange V2	58	50	3
Distal Phalange V3	60	50	3
Distal Phalange V4	61	50	3
Distal Phalange V5	63	50	3
Medial Phalange V5	57	50	3
Proximal Phalange V5	70	50	3
Palm	873	20	5
Forearm	4320	20	5

Table 4: 3D- Printing data of the prosthetic arm.

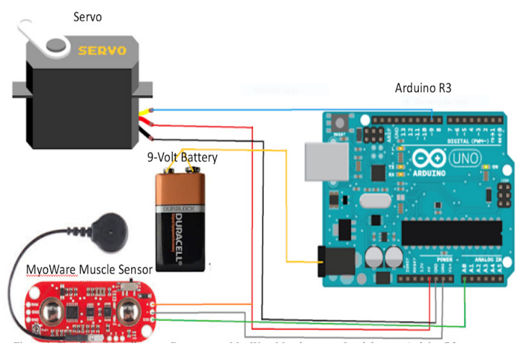

Figure 6: Circuitry wiring diagram, Components: MyoWare Muscle sensor, 9-volt battery, Arduino R3, servo motor.

Color	Length (cm)	Function
Orange	30	Sensor power to Arduino 5 Volt, splits into orange for parallel circuit
Gray	30	Sensor ground to Arduino ground
Green	30	Sensor output to Arduino input 0
Red	5	Servo power to Arduino 5 Volt, splits into orange for parallel circuit
Black	5	Servo ground to Arduino ground
Blue	5	Servo PWM to Arduino PWM 9
yellow	8	9 Volt battery to Arduino power supply

Table 5: Electrical circuitry involving servo motor, 9 Volt battery, Arduino and MyoWave Muscle Sensor.

Table 5).

Arduino

For this myoelectric prosthetic arm, the Arduino interpreted the sensor data from the MyoWare Muscle Sensor and activated the servo at the appropriate time to close or open the hand. The muscle sensor constantly sent sensor values to the Arduino. During a muscle contraction, the muscle sensor sent significantly higher values. The Arduino interpreted these higher values above a set threshold as a contraction of the muscle in the residual limb and triggered the servo to open or close the hand. The Arduino was powered by a 9-volt battery. The graph demonstrating the sensor values over time with spikes exceeding the threshold during a muscle contraction is demonstrated in **(Figure 7)**.

Initially, each value of the sensor was intended to correspond to a different radian of the servo; much like a potentiometer works in the Arduino example servo code "knob." In this scenario, the fingers would be able to be gradually closed and opened by contracting the muscle a slight amount. When plugged into Arduino sensor example code "analog in out serial," the sensor revealed that during a muscle contraction, the user was unable to cause a gradual increase in sensor values by gradually contracting a muscle. Therefore, it was determined that a user could not control the fingers with enough accuracy using this code.

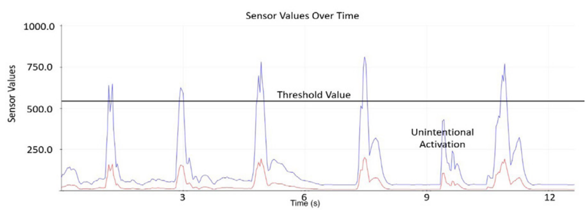

Figure 7: MyoWare Muscle Sensor values over time.

The second iteration relied on a threshold value. This simple code activated the servo to close the hand only when the sensor sent a sensor value over a certain number, which would indicate a muscle contraction. This provided satisfactory results; however, often even when at rest, the sensor sent values that suggested a muscle contraction despite the muscle being at rest. To combat this inaccuracy, a new code was made that averaged the values collected over 500 milliseconds. The average of these values was compared to the threshold value; if the average value exceeded the threshold value, the servo arm would turn and close the hand. This third version nullified almost all random unintentional activations of the servo. Though this code worked, the resting and flexing ranges vary from person to person. Therefore, calibration was required for each new user. Each unique threshold value was found by using a modified form of example code "analog in out serial," which graphed each user's resting and flexing values over time.

Servo

The servo used in this project is a 5-Volt servo motor. The fishing lines, or "tendons," were threaded through the fingers, palm, and forearm and attached to the arm of the servo, located on top of the servo. When activated, the servo arm rotated 180° to shorten the fishing line and close the fingers. To return the hand to its open position, the servo arm returned to its original position, releasing the fishing line, and the orthodontic bands pulled the fingers back into place. **(Figure 6, Table 5)**

Circuitry

The muscle sensor had a power, ground, and output wire. The sensor power and ground wires were connected to the Arduino's 5-Volt and ground ports respectively and were wired in parallel with the servo's power and ground ports. The sensor's output wire was joined to the Arduino's input 0 port. The servo had three wires: a power, a ground, and a Pulse-Width Modulation (PWM) wire. The servo's power and ground wires were attached to the Arduino's 5-Volt and ground ports, respectively. The servo PWM wire entered the Arduino PWM 9 port.

(Figure 6) demonstrates the electrical connections between the sensor, Arduino, servo, and 9-Volt battery. The color-coded lines and their corresponding electrical connections are reflected in **(Table 5).**

Vibrotactile Feedback

The vibrotactile feedback mechanism was independent from the Arduino circuit. It was a simple circuit that consists of a touch sensor, AAA battery, and vibrating motor from a mobile phone. The touch sensor was placed on the tip of the index finger of the prosthetic. When triggered, the touch sensor would allow the current to flow through the circuit and activate the vibrating motor attached to the residual limb via a plastic mount inside the forearm. The user would subsequently feel a vibrating sensation on the residual limb which would alert them that the prosthetic has come in contact with an object.

Testing of the Myoelectric Prosthetic Arm with Vibrotactile Feedback

The participant performed each task five times, blindfold and non-blindfolded, with and without vibrotactile feedback. Task efficiency was determined by the time it took in seconds for the tasks to be completed. Failure to complete a task is defined as taking longer than 60 seconds.

The paired sample t-test in Microsoft Excel was used to compare the statistical difference between the presence and absence of vibrotactile feedback in task performance while the participant was blindfolded and non-blindfolded.

Tests Comparing Time for the Blindfolded Participant to Perform 3 Functional Tests Using the 3D-Printed Myoelectric Prosthetic Arm with & without Vibrotactile Feedback

1) The participant was asked to determine if the index finger with the tactile sensor was being touched.
2) The participant was asked to determine if a plastic block was placed on the palm.
3) The participant had to locate a plastic block on the tray.

Tests Comparing Time for the Non-blindfolded Participant to Complete Eight Daily Tasks Using the 3D-Printed Myoelectric Prosthetic Arm with & without Vibrotactile Feedback.

1) Pick up a coin
2) Cut food

3) Pick up a light object (plastic block, 20g)
4) Pick up a heavy object (stapler, 500g)
5) Hold a cup
6) Pick up a bottle and transfer it onto a tray
7) Hold a tray
8) Squeeze toothpaste on the toothbrush

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