Assistive Paintbrush Device for Limited Dexterity Artists

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ABSTRACT

The CDC reports that 1.7% of Americans have difficulty holding and gripping small objects.[1] These individuals with limited dexterity typically experience a lack of independence when using objects such as paintbrushes, eating utensils, pens, and pencils. Art Therapy Express (ATE) is an art therapy organization in Wilmington, Delaware that aims to give these artists the independence they need to express themselves creatively. Many of their artists include people with physical disabilities, such as Cerebral Palsy or Muscular Dystrophy. Unfortunately, these artists often struggle to paint on their own, and current solutions do not effectively address the struggles they face. Specifically, artists face difficulty in holding and moving a paintbrush by themselves, inhibiting their ability to paint freely. Therefore, there exists a need for better assistive paintbrush devices to give these artists the independence they deserve. This project details the design of a new paintbrush device that will greatly aid ATE patients in their creative endeavors. The device consists of a hand grip, brush holder, and ball-and-socket joint controlled by a joystick controller. The user inserts their hand into the grip, and can control brush position by moving the joystick with their non-painting hand. This design allows the artist to both switch paintbrushes and adjust brush position with ease. Additionally, it is compatible with multiple brush sizes and hand sizes, portable, durable, and cost effective. This report describes the entire engineering design process used to develop this device, and explains how it is an effective solution to create independence for ATE artists.

INTRODUCTION

Motivation & Problem Definition

According to a survey performed by the United States Center for Disease Control (CDC) in 2018, 1.7% of American adults report difficulty gripping or utilizing small objects.[1] These individuals with limited dexterity are unable to independently and confidently use objects such as paintbrushes, eating utensils, and writing utensils. A study of 63 stroke patients showed that a lack of independence is strongly correlated to increased depression and a decreased quality of life.[2]

Art therapy organizations, such as Art Therapy Express, Inc. in Wilmington, Delaware, work alongside individuals with physical and/or cognitive disabilities, such as Cerebral Palsy, to help the artists better express themselves. These individuals often also have limited dexterity, which makes practicing art therapy increasingly difficult. These artists often participate in workshops where painting, drawing, sculpting, and other art forms are available to explore. Artists who need physical assistance are helped by aids to display to the world what is in their mind in a creative way. Art therapy has proven to be a very effective method for improving intelligibility in practicing artists, resulting in improvement in tempo, volume, and control of pauses in speech of participating individuals.[3] Increased intelligibility ultimately increases autonomy and therefore increases quality of life.

Although art therapy has proven effective in improving physical limitations, Art Therapy Express and its artists have communicated their wishes for a more independent experience, especially for artists with limited dexterity. Currently, these artists require a great amount of aid throughout the duration of their therapy sessions in order to grip and maneuver a paintbrush. It is important for the participating artists to create their art independently, so that their art is what the artist intends it to be, and not someone else's interpretation of what they think the artist intends it to be. Independence will ultimately lead to a greater sense of pride in the artists. Creating art independently will also enable the artists to express themselves more freely. As found in the study with the 63 stroke patients, we expect this increased independence will lead to increased happiness and quality of life.[2]

Artists with limited dexterity face a number of challenges while practicing art therapy. The most inhibiting of these challenges comes in the forms of gripping paint brushes or other art utensils, and maneuvering the utensil in the manner the artist intends for it to be moved. Artists often require aid in the form of someone holding the paintbrush with them, using an assistive device that makes gripping the paint brush easier, or a combination of the two. Current solutions, such as those shown in **Figure 1**, include assistive devices aimed to make gripping an art tool easier for the artist. Although current solutions incorporate features for easier gripping mechanisms, they do not allow for angular adjustability of the paint brush, easy adjustability to different paint brush sizes, and full independence of the artist during use. We plan to increase independence of artists using an assistive paint brush device by creating a design that focuses on adjustability and compatibility, while maintaining safety, ease of use, portability, and durability.

Background & Benchmarking

Current assistive devices such as the Sammons Preston T-Bar Holder, [4] the Universal Art Tool Holder, [5] and the Stirex Ergonomic File and Paintbrush Holder [6] (all shown in **Figure 1**) include attachments to make gripping and maneuvering paint brushes easier. These solutions often have an enlarged handle or a sleeve to put over the hand/arm. For example, the T-Bar uses a larger PVC to increase the gripping area, but does not include an adjustable component that allows for different sized paint brushes to be inserted like some other devices do. Although the materials used allow the T-Bar to be extremely portable (measuring only 2.5" in length), the device is hard to the touch and not aesthetically pleasing. Similar to the T-Bar, the Universal Art Tool Holder allows for an easier gripping mechanism because the artist does not have to grip the device at all. The sleeve allows for adjustability to different hand sizes, but doesn't allow the paintbrush to change angles relative to the palm. The adjustability of the paintbrush angles is also a problem with the Stirex Ergonomic File and Paintbrush Holder due to the way the paintbrush is secured. This durable device does allow for different sized paintbrushes, but is extremely rigid and could be difficult for some individuals to grip. Although the current solutions are able to address some of the problems individuals face, no one device was able to cover all of the challenges.

Current solutions do not allow for independence and confidence in artists with limited dexterity. The current devices usually do not allow for different paint brush angles during use, are difficult to change brushes of different sizes out, or simply do not allow the artist to use the device without additional assistance. These devices are also usually rigid and unpleasant to the eye. Members of Art Therapy Express have expressed their desire for comfortable materials as well as a visually stimulating design.

Figure 1: Current assistive devices for artists with limited dexterity. From left to right, the Sammons Preston T-Bar Holder,[4] 2.5,Universal Art Tool Holder,[5] and the Stirex Ergonomic File and Paintbrush Holder[6] are pictured. The Sammons Preston T-Bar features a built up T-Bar grip and is made of PVC that the paintbrush is inserted into. The Universal Art Tool Holder features a hand sleeve with an adjustable cuff around the palm that has an attachment for a paintbrush to fit into on the palmar side of the hand. The paint brush is held perpendicular to the palm. The Stirex Ergonomic File and Paintbrush Holder features a pistol grip with adjustable clamps that hold a paintbrush in place parallel to the top of the grip.

Project Goal

A way to address the lack of independence utilizing an art instrument for artists with limited dexterity in order to reduce the amount of aid needed.

Wants, Constraints, and Metrics

The wants, constraints, and metrics defined in **Tables 1 and 2** below were developed based on the Statement of Work provided by the sponsor, Art Therapy Express.[7] Wants were prioritized based on sponsor specifications, as well as benchmarking design aspects of similar products. Within the metrics table, all target values were set based on engineering standards, literature references, or benchmarked products and justifications can be found within **Appendix A and B**.

Constraints

- **Safety:** The device cannot be sharp or provide the user with a pinching sensation and must be soft to touch and free of materials that are common allergens.
- **Compatibility:** The device must be able to fit various hand sizes as well as fit multiple brush sizes.
- **Adjustability:** The device should allow for variation in the angle at which the paintbrush can be held. There must also be a locking mechanism to secure the paintbrush at a given angle.

Wants

1. **Low Cost of Production:** The cost to manufacture each device must be comparable with the cost of current products existing on the market.
2. **Lightweight:** The device is not heavy and is easy to hold, use, and carry.
3. **Portability:** The product can be easily carried from one place to another.
4. **Durability:** The product will last for a long period of time without breaking and can be reused multiple times.
5. **Easily found replacement parts:** In the case of damage, the product's parts are easily accessible online or fixed easily to where the product does not require special assembly instructions.
6. **Easy to use:** The device does not require much instruction to use and the user feels at ease and comfort while using the product.
7. **Easy to clean:** The device is waterproof and paint does not remain on the bristles following a thorough cleaning.
8. **Aesthetically pleasing**: The device has a colorful, streamlined look that is appealing to the eye.

Table 1. Design constraints with associated metrics.

Constraint	**Description**	**Target Value**	**Reference**
Safety	Cannot be sharp or provide a pinching sensation	Greater than 400 on the BESS scale	[7]
	Must be soft to touch and allergy friendly	No use of latex, acrylics, formaldehyde as are common allergens	[8]
Compatibility	Fit various hand/limb sizes	Length: 4.4 - 7.6 in Breadth: 2.0 - 3.5 in	[9]
	Fit various paint brush types/sizes	Length: up to 12” Width: up to 1.5”	[10]
Adjustability	Allow for different angles at which the paint brush can be held	Maximum 60° wrist flexion and extension, 20° radial and 30° ulnar	DSHS 13-585A [11]
	Secures into place	Pass/Fail	[12]

Table 2. Prioritized design wants with associated metrics.

Priority	Want	Description	Target Value	Reference
1	Low Cost of Production	Cost of production must be comparable to current products on the market	$50 for cost of production	[4]–[6]
2	Lightweight	Not heavy, easy to hold/carry	8 oz.	[4]–[6]
3	Portability	Easily carried from one place to another	Maximum length of 1 ft	[4]–[6]
4	Durability/Reusable	Will last for a years length of time without breaking, with intended weekly use	Ability to withstand elastic deformation when testing stress vs. strain 52 times, with an applied stress of 250 kPa	[13], [14]
5	Easily found replacement parts	Replacement parts are accessible and easily purchased by any user. Requires limited processing after purchase	Can be ordered on Amazon (Pass/Fail)	[15]
6	Easy to use	Does not require a great deal of instruction to use, artist feels at ease and comfortable while using the product	>4 on Artist Survey in **Appendix C**	[16]
7	Easy to clean	Paint does not stick to the product and washes away after cleaning	Visibility of paint after cleaning, 2 or less on Visibility Scale (**Table 4**) in **Appendix C**	ASTM D5913-96 [17]
8	Aesthetically and sensory pleasing	Colorful, streamlined look	>4 on peer survey in **Appendix C**	[16]

CONCEPT GENERATION & SELECTION

Preliminary Concepts

During our initial brainstorming sessions, we used ideas from various other products to inspire our designs. We applied concept generation benchmarking to help facilitate the creation of viable design options from the start. When thinking about different locking mechanisms that would allow for adjustable paint brush sizes, we thought of the velcro straps on tennis shoes as well as the screw fastener on a christmas tree stand. We also wanted to incorporate a grip that is easier to hold than a small paintbrush and thought of the grip on a shovel with ridges for the fingers as a great place to start. Another product that inspired a grip idea for us was a bendy ruler. We thought this material would allow for a great deal of adjustability and allow the user to wrap the device around their hand/arm however they would like. Together, these ideas inspired some of the components of our preliminary concepts.

Our team used both system-level and component-level design during our concept generation. We first developed designs on the basis of systems. We then came together to discuss these systems and realized that most of them had similar components within the different systems. We then broke the systems down into their components based on that conclusion. We identified what we thought were the key components to a successful design and eliminated ones that we agreed were not as important or would inhibit the success of our design. We then went through each component that we kept and identified the options from our system-level designs. We also discussed other options and added them in if we thought they would be beneficial. Based on this information we agreed upon, we each went back to create systems that included a variation of each of the components we discussed. Finally, we came back together with system-level designs, narrowed in on the three we liked best, and included those concepts in our decision matrix. We found this approach extremely beneficial because we were able to identify what we all thought were important aspects to include in our designs, but were then able to use our individual creativity to combine those aspects in unique ways.

Concept 1: Flexible Grip Brush

The first concept is the flexible grip brush (**Figure 2**). This is a unique design that gives the user ease in regard to grip and brush size. The grip is composed of a bendable plastic surrounded by a soft foam and/or gel. Due to its elasticity, it can be wrapped around the hand in whatever way the user desires. The goal is that the user can put on the grip themselves. However, given the severity of their condition, they may need help from an assistant. The grip's flexibility makes it customizable, and helps the user grip the brush in the way that is easiest for them. The top of the grip contains a velcro strap for the paintbrush to fit snugly on the device. The velcro is adjustable, allowing for multiple paint brush sizes. Again, this is designed so that the user can change it themselves, but they may need additional assistance. This design is unique in that it allows the grip to be bent in any direction, unlike similar brushes on the market that are only used in specific shapes, such as a coil. This concept solves the problem by providing an adjustable and customizable way to hold a paintbrush. Currently, artists at ATE struggle with holding their brushes independently. A bendable grip gives them the opportunity to hold the brush however they want.

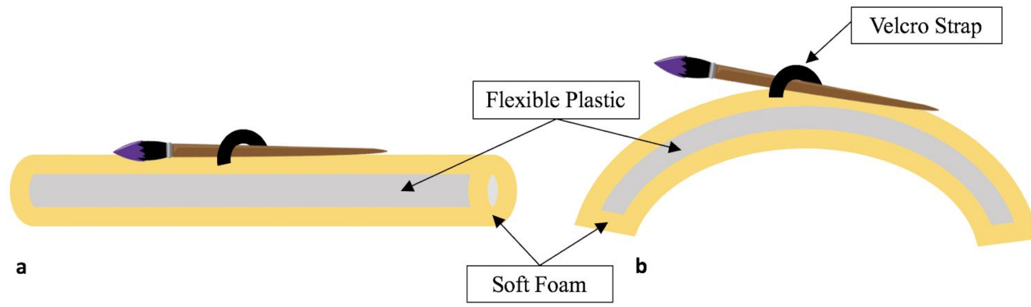

Figure 2: Brush attaches into adjustable a velcro strap, allowing for multiple brush sizes. The grip consists of flexible plastic material that is bendable in multiple directions. It is wrapped in a soft gel or foam to allow for a more comfortable grip. The grip can be wrapped around the hand and molded in whichever direction is most comfortable for the artist (2b).

Concept 2: Roller Hand Brace

The second preliminary concept is the roller hand brace, which is a hand brace with a roller that lies along the top of their palm (**Figure 3**). The user independently puts on the hand brace as if they were putting on a glove and uses the curl of their fingertips to facilitate the movement of the roller. The roller is attached onto the glove using a pin joint at each end, and an interlocking cylindrical holder is hinged onto the roller in between the user's middle and ring finger. The hinge joint allows for greater variation in the angle of painting. The brush is inserted into the holder, and is secured using a locking screw that is tightened by the user. The brace itself can be tightened by the user using a velcro strap. Users at ATE experience difficulty raising their arms in the vertical direction. By allowing translation of the paintbrush up and down in the vertical direction, the roller mechanism rewards the user with a greater range of motion. The device also allows for the brush to be secured into place, allowing the user to paint without fear of dropping their brush.

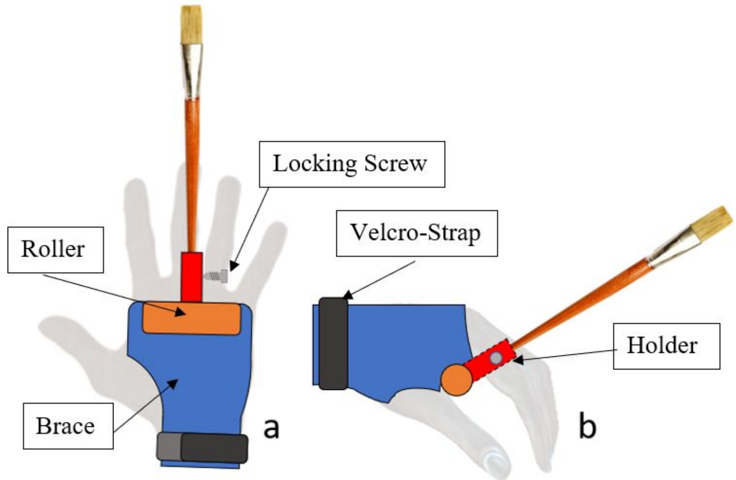

Figure 3: The user inserts the brush into the red holder and tightens the locking screw to secure the brush. Roller pictured in orange. 3a represents the hand brace with the palm side of the hand facing up. 3b represents a side view of the roller, the user rolls with fingertips and the paintbrush moves accordingly. On the wrist lies a velcro strap that allows the user to tighten and loosen the brace.

Concept 3: Hand Grip with Ball-and-Socket Joint

The third preliminary concept is the ball-and-socket joint with a hand grip (**Figure 4**). It contains a soft grip with ridges so that the user's fingers sit comfortably, similar to a shovel. The grip is attached to a ball-and-socket joint, where any paintbrush can attach. The joint will be manufactured so that the ball fits snugly in the socket, providing enough friction so that it does not slide. However, the brush can be moved at any angle by pushing the brush, and thus moving the joint. The user can do this themselves, or ask for assistance if needed. The paintbrush can be changed with a locking screw that adjusts based on paintbrush diameter. The locking screw is tightened by the user. This design allows the brush to be moved at any angle whatsoever, making it easy for the artist to change the angle at which they are painting. Additionally, it gives the artist something to hold other than a physical paintbrush. It will be easier for ATE patients to hold the hand grip, where their fingers will fit nicely into the ridges.

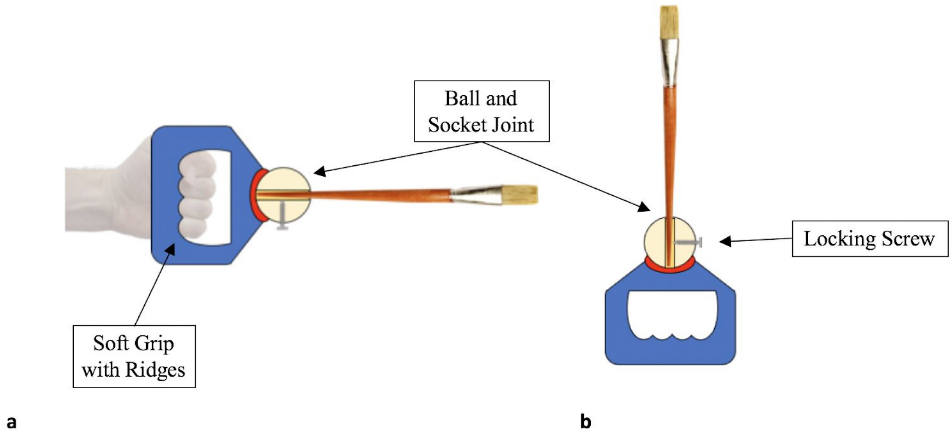

Figure 4: The user holds the brush with a comfortable grip with ridges for fingers to fit nicely (4a). Brush size can be changed with the locking screw. The brush sits in a ball-and-socket joint that allows it to move in any direction.

Concept Selection

We used a weighted decision matrix to aid us with our concept selection (See **Appendix D, Table 5**). We had three very different ideas, all of which seemed like viable options. Our decision matrix took into account the wants described above, and they were weighted appropriately based on the priority they were given. We did not include the constraints in our decision matrix, because they are non-negotiable and therefore each design already fits the constraints. After weighting the criteria, we gave each design a score from one to ten for how well it fit each want. This was a lengthy discussion full of debate, as we wanted to consider as much as possible before making any decisions. During this conversation, we researched prices to help estimate cost of production, determined places to buy replacement parts, and thought about each criteria in detail. This helped us give good, accurate scores to each design and made sure we did not go in with prior bias.

After evaluating each of the products by using the decision matrix, the flexible grip brush had the highest overall score. Specifically, it ranked highest in cost of production, lightweight and portability, and ease of use. This concept is the simplest, and requires the least amount of machining. Additionally, the materials needed are all very inexpensive, which is why it ranked highest for cost of production. This product is the most lightweight, because both plastic and foam are very light. Concepts 2 and 3 both include adjustable screws, which would be heavier. They are also bigger products, which would probably make them heavier. We also decided it was more portable because its flexibility would allow it to be carried easier. Finally, we gave it the highest score for ease of use because it is the simplest design. It may be difficult for artists to deal with the roller or the ball-and-socket joint.

Based on our decision matrix, we originally proposed to move forward with Concept 1, the flexible grip brush, as we felt it was the most viable concept to bring into Phase 3. However, after further discussion following the completion of Phase 2, we felt this design needed to be enhanced to allow for greater independence to the artist. Therefore, a new design was developed that takes some components from our previous design ideas and combines them with additional components to achieve a design that will benefit the artist in a much more profound way. For example, the base of our new design is an improvement on the flexible grip brush. Instead of a single, long piece of bendy material that the artist, or more likely an aid, will have to struggle with to wrap around the artist's hand, we have modified to an "X" shape that still utilizes this very adjustable material. The new base will also include mesh for the artist's fingers to slide through as well as an elastic band that will be placed around the user's wrist. This more rigid approach will ultimately allow for more stability, comfortability, and independence for the artist. After many more brainstorming sessions like this, we feel as though we have arrived at a more sophisticated design that focuses on artist independence while using the device.

Broad Impact of Design Solution

Due to the product's intended use of being wrapped around the hand, the user does not have to paint with the fear that the brush will fall from them in the case of a sudden spasm. This product helps to bring independence and security to the community suffering from limited dexterity, such as those with cerebral palsy. With this new innovative device, the users can return to performing art therapy with ease. Art therapy has its own benefits, as reflected in a 2010 study which exposed 14 children with Cerebral Palsy to art therapy for a period of 4 months and saw improvement in all of the children's overall intelligibility, with significant improvement ($p<0.001$) in the tempo, volume, and control of pauses within their speech.[3] With our device, we help reward the artist with independence, while also helping to improve their conditions using art therapy.

This product should be accessible to those in need all around the world. By keeping a low cost of production for the device, we can assure that this product is affordable without the need of medical insurance or other healthcare providers. Although having a low cost of production, this product still brings the user the value of independence, as well as quality materials. Similar adaptive paint brushes are priced around $30 for each product, yet fail to reward the user with a wide range of painting motion.[4] Our product is expected to cost $43.10 to produce (see **Table 6**). The ABS plastic chosen for this product is relatively inexpensive as compared to other plastics, costing an average of $1.50 per pound.[18] In addition to being cost effective and accessible, this product also proves to be eco-friendly. Most plastics are not biodegradable, yet they can be reused and recycled.[19] The base of this product is a plastic that can be easily cleaned and reused, with a lifelong shelf-life. Eventually after years of wear and tear, if the user chooses to dispose of the product, they can recycle it and the plastic will be treated to create another reusable product.[19]

FINAL DESIGN

The concept of this design involves the user navigating their paintbrush using a joystick which controls two servo-motors (x- and y- movement) that are built into a hollow ball-and-socket joint. The design consists of a Polylactic Acid (PLA)-cross hand grip, an ABS-plastic ball-and-socket joint, an ABS-plastic brush holder, and an electronic motor with a joystick remote that controls the movement of the ball-and-socket joint (see **Figure 5**). The user puts the device onto their desired painting hand by sliding their fingers through an elastic compressive mesh and an elastic band located on the cross hand grip. The elastic compressive mesh is located below the cross hand grip, and secures the device around the palm of the hand. The elastic band is located on the rear of the cross hand grip and secures the device around the user's wrist. Atop the cross hand grip lies the ball-and-socket joint, and atop the ball-and-socket joint lies the cylindrical brush holder. Once the device is secured on the hand, the user takes their desired brush and places it into the cylindrical brush holder, then pushes the button that lies on top of the cylindrical brush holder. This button clamps the brush into place and will remain locked until the user pushes it again. On their non-painting hand lies a remote control with a joystick, which communicates with the circuit inside of the ball-and-socket.

With the current prototype, the circuit within the ball-and-socket is wired to the joystick. The joystick's movement is responsible for the motion of the paintbrush - forward corresponds with movement in the +y direction, backwards corresponds with movement in the -y direction, leftwards corresponds with movement in the -x direction, and rightwards corresponds with movement in the +x direction. Motion of the joystick in a direction such as 45°, corresponds with joint movement in the x and y directions, allowing for angled painting and enhanced adjustability. When the user wants to change their paintbrush, they simply press the button atop the cylindrical brush holder and the original brush can be removed. This mechanism allows for increased compatibility with different brush sizes. Once the user is finished painting, they can remove the device by sliding the cross grip off of their hand and turning the joystick remote control off. This design rewards the user with enhanced independence, as they do not have to rely on another person to change brushes, control their direction of painting, or to put on/remove the device from their hand.

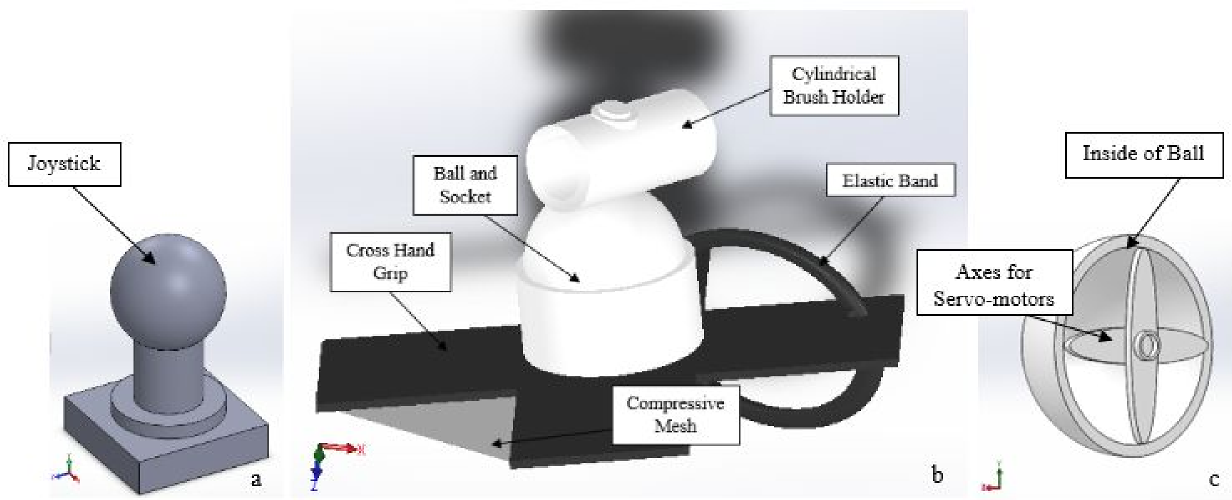

Figure 5: 3D rendering of the final design. User puts on the device by sliding their hand through the elastic band and compressive mesh, and then bending the ends of the cross hand grip onto their hand (5b). The user then inserts the brush into the brush holder and pushes the button to secure. To facilitate movement, the user moves the joystick (5a) which controls two x-y servo motors within the ball-and-socket (5c).

Design Details

The cross hand grip provides support, comfort, and adjustability to the artist while maintaining independence when gripping and maneuvering the assistive paintbrush device (see **Figure 10**). The grip consists of an “X” shaped strap made of armature wire covered in PLA to allow the material to bend and maintain its shape once bent into the desired position, a wrist strap with specifications similar to a standard elastic hair tie, and a mesh support for the user’s fingers see **Figure 11**). The size (detailed calculations and dimensions in **Appendix E**) of the “X” strap is not too bulky for the smallest hand sizes, yet will still be able to wrap around the sides of larger hands. The elastic wrist strap used will provide comfortability because it is the same size (thickness of about 0.2” and diameter of 1.8”) and material as a standard hair tie, which is often worn around people’s wrists for a whole day or even longer. The 0.25” diameter holes for the elastic strap to run through allow for the strap to be easily replaced if it breaks or gets worn out. The compressive mesh on the opposite side of the “X” strap is held in place by epoxy. This material will provide support to the fingers, but allow for the user to easily slip the device onto their hand. Overall, the shape and features of the cross hand grip allow for independence, comfort, stability, and adjustability.

The cross hand grip is attached to a ball-and-socket joint that controls the brush’s movement (see **Figure 12**). The ball is a hollow sphere with an inner radius of 0.8’ and an outer radius of 0.9”. The ball sits in a cylindrical shaped socket, with a radius of 1.0” and height of 1.0”. The size of the cylindrical socket was chosen to be small enough to fit on the hand and also sit firmly on the hand-grip base. Both components are made of ABS plastic, because it is easily 3D printed and will provide seamless integration with the rest of the device via an epoxy glue. The ball-and-socket joint is attached to the cylindrical brush holder described below via an epoxy glue, giving it the ability to move the brush in any direction.

The ball’s movement in the joint is controlled via a joystick connected to an Arduino circuit (See **Appendix F** for Fritzing diagram and Arduino code). Within the hollow sphere lies two elliptical axes, arranged in an X (see **Figure 13**). These axes are also made of ABS plastic, and attach to two servo-motors that work with the Arduino circuit. Each servo motor has a range of motion of 180° and a stall torque of 1.8 kg/cm (161.3 oz/in). This is strong enough to move the ball-and-socket joint, and gives the paintbrush a full range of motion for the artist. An Arduino circuit was chosen because they are easy to create and commonly used for similar applications (see **Figure 14**).

The joystick component of the device is grounded and controlled by the user’s non-painting hand. It allows the user to control the direction of the device while the user paints. The underlying joystick is a standard Arduino joystick, yet there is a larger, adaptable ABS coated joystick that is easier for the user to grip and maneuver with their palms rather than their fingertips (see **Figure 15**). The adaptive joystick has a spherical grip that is 1.54” in diameter. The coating is of ABS plastic and was chosen since the plastic is strong, smooth to touch, and easy to clean. Since the base needs to be large enough for the Arduino circuit connections to run through, it was designed to have a size of 2” x 2” x 0.5”. The structure of the joystick was designed to help make control easier for users with limited dexterity.

The cylindrical brush holder sits atop the ball-and-socket joint and is intended to secure the brush onto the device. The device is made of an ABS Plastic hollow cylinder as the base, with an internal stainless steel locking mechanism. ABS was chosen as the base due to its ability to be 3D printed and compatibility with epoxy glues. Stainless steel was chosen as the locking mechanism through benchmarking of similar locks. The cylinder is 2” long since that is the average size of the dorsal side of a hand.[9] When the user begins painting, they simply place their brush within the holder and push the button to lock into place. As the user pushes the button, a latch pushes the brush against an extrusion (see **Figure 16**), securing the brush into place. When the user is finished painting and wants to remove the brush, they simply push the button and that releases the lock. This simple push button method rewards the user with increased independence. The referenced push button is “Push Button Switch Latch Replacement For Boat Door Glovebox Southco 93-30”.[20]

Detailed technical descriptions, justifications, and engineering drawings of each individual component can be found in **Appendix E.**

Proof-of-Concept

Our first proof-of-concept was testing the circuitry involved with the joystick. This was to evaluate the validity of our design and confirm that the brush position could be controlled via the joystick using an Arduino circuit. To do this, we used TinkerCAD, an online 3D modeling program that also allows you to build and simulate Arduino circuits (see **Figure 6**). Additionally, we created a Fritzing diagram of the final design and wrote an Arduino code for the device. These tests confirmed that there were no issues in our design, and that if we were to physically build the circuit, all components would work correctly.

The first portion of this process was simulating the circuit in TinkerCAD. Unfortunately, TinkerCAD does not have a joystick module available for their simulations. Therefore, we were forced to use two potentiometers, where each one controlled the movement of one of our servo-motors. These servo-motors correspond to movement of the ball-and-socket joint along the x- and y- axes in our final design. While this is not what our final design would look like, we considered it valid because the chosen joystick module is just a combination of two potentiometers. The TinkerCAD simulation worked smoothly, and showed that moving the potentiometers easily controlled the servo-motors’ movement. The full TinkerCAD circuit, with completed wire connections and all components labeled, is shown in **Figure 6**. Following the TinkerCAD simulation, we built a circuit that incorporated the chosen joystick module using Fritzing software (see **Figure 13** in **Appendix E**). After finishing the circuit, the software confirmed there were no unrouted connections, and that it would work if it was physically built. Additionally, we wrote an Arduino code to correspond with the circuit, which did not have any errors when tested. A full copy of the Arduino code is available in **Appendix F.**

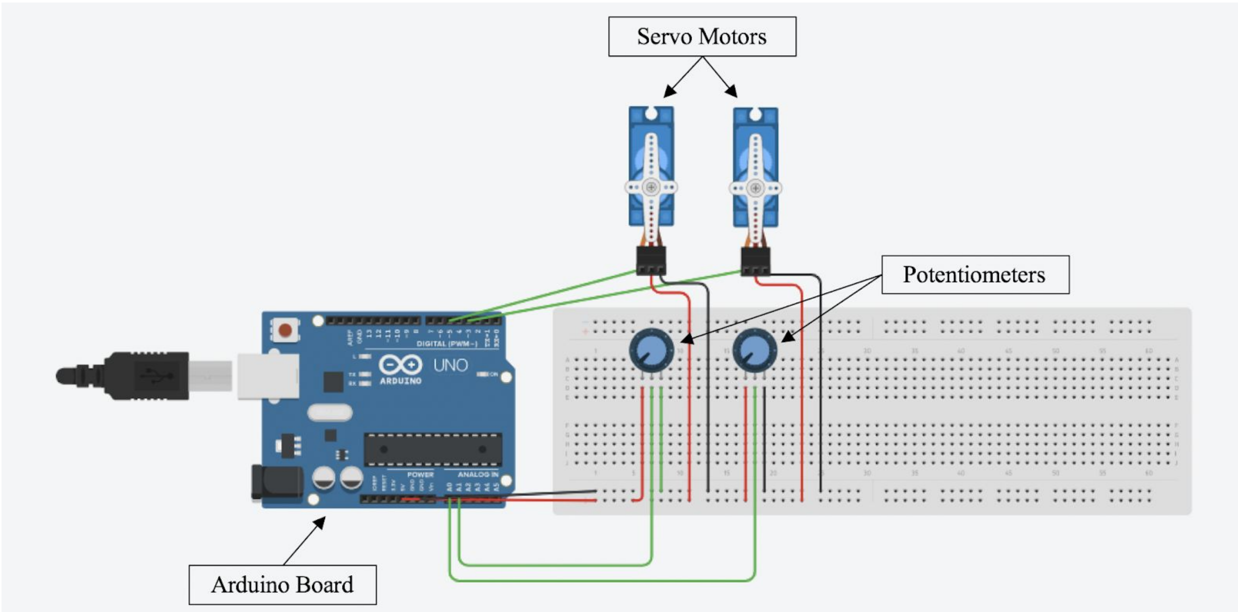

Figure 6: Proof of concept circuit created in TinkerCAD to simulate servo motor movement. This differs from the final design because the servo motors are each controlled by a separate potentiometer, as opposed to a joystick. Circuit was adapted from a similar Arduino project.[21]

The completion of these simulations was proof that our concept will work. However, this differs from the design in a few ways. Firstly, we could not actually confirm that the joystick module works, and had to substitute the use of two potentiometers. Additionally, this does not show the device how it will actually be built. In our final design, the two servo-motors are stacked on top of one another, inside the sphere of the ball-and-socket. The ball is hollow with two axes running through it, with spots for the servo-motors to attach (See detailed engineering drawing in **Appendix E**). We also hope that we can convert this circuit to a wireless design based on Bluetooth. However, given the current circumstances we were not able to build and test this.

Since we could not improve upon the circuitry proof of concept any further following Phase 3, we decided to prototype a different aspect of our design - the device's compressive strength. This proof of concept was simulated using Algodoo and aims to test whether the device will rupture when exposed to a normal stress of 250 kPa. With this simulation, we cannot test the strength of each individual component of the design, yet attempt to represent the entire system as a 0.075 m x 0.165 m ABS block (see **Figure 7**). Given that the majority of the device is made of ABS plastic, we look to test the risky assumption that the device will maintain structure when exposed to daily use.

This proof of concept models the device as a 0.075 m x 0.165 m ABS block. These measurements correlate to the height of the device and the maximum length of the device respectively. A rectangle of such size was created and the material properties of density and coefficient of restitution were adjusted to 1.1 g/cm^3 and 1.120 respectively, which are material properties of ABS plastic.[22] A load of 3093 N was applied onto the centerpoint of the block.

This value was calculated by multiplying the 250 kPa of stress by the model's cross sectional area of 0.0124 m^2. A simulation was then performed and it was deemed that the device does not rupture when exposed to this load.

This proof of concept differs from the final commercial design in many ways. For example, the device will not be a block shape, but rather an abstract combination of shapes. This structure would distribute load differently and non-uniformly onto the device. Since stress depends on cross sectional area, it is difficult to apply a stress of 250 kPa in such a way that a uniform load is distributed around the device. Different components have different cross sectional areas, causing different applied loads. In addition, the testing protocol attempts to test the durability of the structure as a whole, which includes the strength of the epoxy glue bonds. Unfortunately with the Algodoo simulation, the strength of the epoxy glue could not be tested.

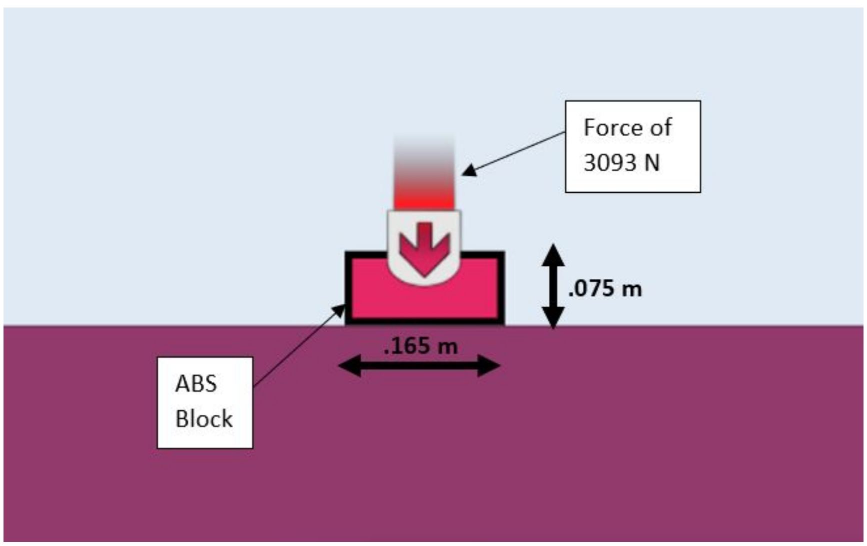

Figure 7: Algodoo simulation of compressive strength. 3093 N force corresponds with a stress of 250 kPa with normal use. The dimensions .165 m and .075 m represent the length and height of the ABS block respectively. Block was chosen to model the device for testing simplicity.

Anticipated Cost

The anticipated cost to produce the final design is $43.10, with the bulk of our expense coming from the circuitry used to maneuver the device. Products were analyzed from a variety of different vendors, such as McMaster-Carr, DigiKey, and Mouser, yet ultimately the majority of our parts were ordered from Amazon and Banggood (see **Appendix H**). Most of the products were ordered in singularity, yet a few had to be ordered in bulk, even though our design only used a small fraction of the product. These products include PLA filament, Armature wire, jumper cable wires, servo-motors, batteries, and ABS filament. Overall, the cost of this design satisfied the metric of less than $50, and achieved a low cost of production.

DESIGN VERIFICATION & VALIDATION

Failure Analysis

After completing design failure modes and effects analysis, a few potential failure mechanisms have been identified. For example, one possible failure lies within the cylindrical brush holder. There is a high risk involving the brush not securing, whether that is caused by a button jam or by an irregular sized brush. If this occurs, the device becomes no longer functionable. To mitigate this risk, we ask for the user to oil the lock with every 10 uses to assure the lock stays lubricated and does not jam. Likewise, we have established a testing protocol for different size and shaped brushes (see **Appendix I**) that will determine which brush sizes work best and which do not. If any brush size fails, we would have to remodel our cylindrical brush holder to accommodate this.

Another potential mode of failures is the epoxy glue failing to uphold the components together. This could be observed at the junction between the ball-and-socket joint and the cylindrical brush holder, as well as in the components of the cross hand grip. If this were to occur on the ball-and-socket, it would become detached from the cylindrical brush holder. While the ball-and-socket still would work properly, it would have no way of controlling brush angle. Likewise, if this failure was to occur on the cross hand grip, the mesh would separate from the "X", meaning the user's fingers would not be secured and the device would become less stable on the artist's hand. To mitigate the risk of epoxy glue failure, an Instron will be used to perform tensile strength testing of this portion of the device. If the testing shows that the epoxy does not hold the materials together, a stronger epoxy or a different mechanism will be tested and used in an attempt to eliminate this failure mode.

A third failure mode concerns the circuitry used to control brush movement. If the wires break, the connections are not secure, the breadboard breaks, or the motors stop moving, the brush's movement would no longer be controlled by the joystick. This would render the device useless. To mitigate this risk, all connections must be checked and properly secured before using the device, and only high quality products will be purchased.

The detailed Design Failure Modes and Effects Analysis table can be found in **Appendix J (Table 12).**

Testing

The functionality of this design was intended to be validated by a series of test protocols described below (see **Appendix I** for full protocols). Although some test protocols were unable to be performed due to unforeseen circumstances, predictions of results were generated based on the design details and metrics justifications (see **Appendix A**). Each test protocol attempted to satisfy a metric defined within the metrics table (see **Table 2**) and several test protocols were adapted from engineering standards. Most testing methods attempted to analyze the entire system, for example, the protocol for testing compressive strength which others analyzed each metric on a component level basis, such as the protocol for fitting multiple brushes and lock security (see **Appendix I**). A summary of the test protocols are as follows.

- **Sharpness:** This test was designed to determine the sharpness of each edge on the device. The testing involves placing each edge of the device onto a Edge-on-Up Professional Edge Tester and comparing the result to a BESS sharpness scale. While we are not able to test this metric, we can predict a BESS reading of greater than 400, which suggests rolled edges. This implies a pass, and reflects that our design does not have any sharp edges and will not cause a cutting injury to the user during regular use.

- **Allergens:** This test was designed to determine if the device contained any common allergens, specifically latex, acrylics, and formaldehydes. Each material on the device was analyzed for containing any of the common allergens, and the result of the test was a pass, meaning the device did not contain any of the allergens. This implies that the device is safe to use and the user will not experience any allergic reaction during regular use.

- **Compatibility of Different Users:** This test was designed to determine whether the device could fit on various hand sizes by testing the minimum and maximum lengths and breadths of hand sizes defined in the metrics table. To do this, two blocks of wood would be cut - one with the minimum hand dimensions (5.4” x 2” x 1”) and one with the maximum hand dimensions (8.6” x 3.5” x 1”). Each block has 1” added to the respective length to enable testing of the elastic wrist band. The device is placed on the block with minimum dimensions with the elastic band around one end, straps around the sides, and mesh around the other end. Observations are made to determine whether all parts fit on the block. This process is then repeated for the block with maximum dimensions. If the device fits both blocks in all areas, the device passes. Although this test could not be performed due to lack of physical materials needed, we know that the dimensions of the device were designed around these different hand sizes. Therefore, we assume the device will pass this test and will be compatible with users of various hand sizes.

- **Fitting Various Brush Sizes and Lock Security:** This test was designed to determine the efficiency of the cylindrical brush holder, by analyzing how well it performs with different brush sizes and shapes. Fifty paintbrushes consisting of five different sizes (10 of each) were tested. Each test iteration consisted of securing the brush in the holder, shaking it for 10 seconds, and removing the brush. Each iteration was judged based on if the brush remained secure after shaking. While we couldn’t physically test the protocol, we can predict a pass based on the design specifications of the cylindrical brush holder. A pass with this test implies that the device is indeed compatible with multiple brush sizes and secures the brush into place, satisfying constraints of compatibility and adjustability.

- **Brush Adjustability:** This purpose of this test was to determine the overall adjustability of the brush’s angle using the joystick controller, corresponding to part of the “adjustability” metric. To test this, users were asked to use the device’s joystick to place the brush at a specific angle (ie. rotated 90° to the left). The test was run on a sample of subjects with no dexterity issues (control), and a sample of ATE patients who are a part of the target population. Subjects were asked to repeat each movement three times, and the error in brush position was calculated using a protractor. We were unable to perform this test, but we predicted an average error of less than 5°. An error this small would indicate the design passes the adjustability metric, as the overall brush movement is much greater than that of a human wrist.

- **Low Cost of Production:** This test was designed to determine whether the cost of production of the device is less than $50. In this test, the list of materials needed to make the device, the amount of each material needed to make one device, and the cost of each material for the amount needed were obtained. The prices for each material were added to obtain the total cost of production of one device. This test was performed with the completion of the Anticipated Cost Analysis. The total calculated was $43.10 which is less than the $50 metric. Therefore, the device passes and is considered to have a low cost of production.

- **Measuring Weight:** This test was designed to determine the weight of the device. It was a simple test protocol that involved weighing the device on a scale and recording the output. Although we couldn't physically test this metric, we can predict a fail due to the device's circuitry adding a substantial amount of weight. This implies that the device surpasses the 8 oz. threshold for weight and does not accomplish the metric for lightweight.

- **Portability:** This test was used to determine if the device is portable and specifically, if the device measures less than our 1' in length metric. To perform this test, the device would be measured in all directions. If the device measures less than 1' in every direction, the device passes. Although this test could not physically be performed because of the lack of a physical prototype, the dimensions of the device are known. The maximum length of the device (length of the cross hand grip) measures 6.5". The height of the device (thickness of cross hand grip + ball-and-socket + brush holder) measures 3". Since both of these measurements are less than 1', the device passes this test and is considered to be portable.

- **Compressive Strength:** This test was designed to determine the overall durability of the device, specifically by testing the compressive strength. The test involved loading the device onto an Instron machine preset to a load of 322.5 N. This load is the calculated load given a stress of 250 kPa which is the anticipated stress applied to the device during regular use. The device is tested 52 times to represent weekly use for a year. At the end of testing, the device is tested for functionality. We predict a pass for this test given the ultimate compressive strength for ABS plastic is 63 MPa. This implies that the product is durable and can withstand wear and tear from everyday use.

- **Replacement Parts:** The purpose of this test was to determine if all replacement parts for the device could be purchased on Amazon to ensure that the user could easily find these parts if needed. To do this, the Anticipated Cost table was used. The items with Amazon listed as the vendor automatically passed while items with a different vendor name were searched for on Amazon. If the item was found on Amazon, the part passed. Since all the items could be found on Amazon, the device as a whole passed and it was concluded that replacement parts could be easily found for the device.

- **Ease of Use and Aesthetics:** This test was developed to test the "ease of use" and "aesthetically and sensory pleasing" metrics. The testing protocol involves the selection of a random group of ATE patients to test the device during one of their regular therapy sessions. After a demonstration on how to use the device, the artist will be free to use it while painting as they would normally. Following the session, they will be asked to complete the "Ease of Use Survey" and "Aesthetics Survey" found in **Appendix C**. An average score greater than four on both surveys would indicate that the device passed. Unfortunately, we cannot test the device on actual ATE patients due to current circumstances. However results would be very beneficial in understanding user feedback.
- **Cleanability:** This test was developed based on an ASTM standard, D5913-96, to test the "easy to clean" metric. Similar to the ease of use and aesthetics test, a random group of ATE patients would be chosen to test the device during their regular therapy sessions. They will be free to use it while painting, as they would normally with other devices. Following the session, the brushes would be cleaned according to regular ATE practice. Each brush/device would be scored by three members of an unbiased third party, based on the paint visibility scale found in **Appendix C**. An average paint visibility of less than two would indicate a pass. This is another test that could not be performed due to current limitations.

Verification & Validation Results

While we were unable to physically test the majority of our metrics, we were able to make educated predictions based on each of the testing protocols. Based on these predictions, we can conclude that this device is successfully able to give artists with limited dexterity greater independence while painting. Tests that were able to pass successfully involved a design analysis, rather than a physical experiment. The test protocols regarding material analysis concluded that the device was free of allergens, low-cost to produce, and contained easily accessible replacement parts, while the test protocol involving size analysis determined that the product was indeed portable. The device is expected to cost $43.10, which is below the metric of $50. Additional cost of the circuitry is justified by increasing adjustability. In addition, the materials incorporated in the device lacked latex, formaldehyde, or acrylics, and all parts were able to be accessed on Amazon.com.

Design details were also incorporated in determining the success of experimental testing protocols that involved. These predicted results conclude that the device fits various hand and paint-brush sizes, allows for different painting angles, secures the brush into place, and will stay durable with regular use, but is not lightweight. Survey-based experimental testing protocols reflect that the device will be easy to use and clean, but may not be aesthetically pleasing. The use of servo-motors within the ball-and-socket allows for 180° motion, which is greater than the regular range of motion of the wrist. Above the servo motors on the ball-and-socket, lies the brush holder with a locking mechanism that effectively secures brushes into place. In addition, the ABS and PLA plastics chosen have ultimate compressive strengths that far surpass the normal stress of 250 kPA, allowing for durability over a year's time. Similarly, these plastics also have a property that resist materials such as paint to stick to. The introduction of components such as the joystick and push button allow for simple movement and suggests the product is easy to use. After consideration of the weight of each of the circuit components, we expect the product to fail the metric for being lightweight, yet these components are justified for increasing adjustability. Future modifications of the design would attempt to reduce the bulkiness of the circuitry. **Table 3** summarizes the project metrics and the results of validation testing, with any tests passed by the final design.

Table 3. Verification Testing Results

Priority	Constraint/Want	Description	Target Value	Pass/Fail
Need	Safety	Cannot be sharp or provide a pinching sensation	Greater than 400 on the BESS scale	Predicted Pass
		Must be soft to touch and allergy friendly	No use of latex, acrylics, formaldehyde as are common allergens	Pass
Need	Compatibility	Fit various hand/limb sizes	Length: 4.4 - 7.6 in Breadth: 2.0 - 3.5 in	Predicted Pass
		Fit various paint brush types/sizes	Length: up to 12” Width: up to 1.5”	Predicted Pass
Need	Adjustability	Allow for different angles at which the paint brush can be held	Maximum 60° wrist flexion and extension, 20° radial and 30° ulnar	Predicted Pass
		Secures into place	Pass/Fail	Predicted Pass
1	Low Cost of Production	Cost of production must be comparable to current products on the market	$50 for cost of production	Pass
2	Lightweight	Not heavy, easy to hold/carry	8 oz.	Predicted Fail
3	Portability	Easily carried from one place to another	Maximum length of 1 ft	Pass
4	Durability/Reusable	Will last for a years length of time without breaking, with intended weekly use	Ability to withstand elastic deformation when testing stress vs. strain 52 times,	Predicted Pass

			with an applied stress of 250 kPa	
5	Easily found replacement parts	Replacement parts are accessible and easily purchased by any user. Requires limited processing after purchase	Can be ordered on Amazon (Pass/Fail)	Pass
6	Easy to use	Does not require a great deal of instruction to use, artist feels at ease and comfortable while using the product	>4 on Artist Survey	Predicted Pass
7	Easy to clean	Paint does not stick to the product and washes away after cleaning	Visibility of paint after cleaning, 2 or less on Visibility Scale in Appendix A.	Predicted Pass
8	Aesthetically and sensory pleasing	Colorful, streamlined look	>4 on peer survey	Predicted Fail

CONCLUSIONS

Design Evaluation

The design met all of the metrics set, with an exception of only two of the wants. Although the design is predicted to fail the aesthetically and sensory pleasing metric, as well as the lightweight metric, these are both defined as wants and all of the constraints of the design are met. "Aesthetically and sensory pleasing" holds the least weight of all the metrics, and the design can be further developed to try to fit this metric. The weight of the device due to the circuitry allows for greater independence of the user, which was the ultimate goal of the design. Therefore, the benefits outweigh the costs. Furthermore, the lightweight want holds the second highest weight of all the wants, but going forward, the materials of the design can be further explored to try to reduce the weight and satisfy this metric. Both proof of concepts of the design passed successful validation, with the circuitry functioning in both the Arduino and Fritzing softwares, and the device being able to withstand a strength simulation in Algodoo.

Deliverables

- The final virtual prototype, which includes 3D CAD drawings, Fritzing diagram, and Arduino code
- Final written design report
- All dimensioned engineered drawings and schematics of design components
- User surveys and testing protocols
- Full cost analysis in **Appendix H**
- Google Team Drive organized with all documents relevant to the design process

- Summary of necessary steps to move forward

Path Forward

Moving forward, we would like to continue to develop our prototype so that it meets all of our constraints and wants. We will explore different materials that can be used to improve upon the weight of the device, so that it will pass the lightweight metric. Additionally, we hope to improve the device so that it is more aesthetically pleasing. Although "aesthetically and sensory pleasing" was lowest in priority, painting the device so that it is more colorful, or creating a more streamlined look will improve overall user experience. Once the current restrictions due to the COVID-19 pandemic are lifted, next steps would also include building a physical prototype and completing testing protocols. This would aid us in creating improvements that we could not foresee, due to the limitations of virtual prototyping. Additionally, we would like to explore bluetooth options to make the device easier to use. Finally, our physical prototype would be tested at ATE in order to receive feedback and complete other testing protocols. Once these steps are completed, we could move forward in implementing this device for actual use at ATE.

Regulatory

If this device were to move forward for regulatory approval, it would be classified under a Class II medical device. Our design is non-invasive, yet the circuitry and mechanics of the device introduce a complexity that makes it difficult to be classified as a Class I medical device. Since our product is not Class III, we do not have to file a Premarket Approval (PMA), yet since it is not Class I, we are not exempt from the Premarket Notification (501(k)). Given the classification, the next step would be to file a Premarket Notification (501(k)) with the Food and Drug Administration.

This premarket submission is intended to prove that our device can be marketed as safe and effective in comparison to a legally marketed device.[23]. Given that we have several products benchmarked earlier in our design process, we can use those to compare and create equivalence claims to the FDA. Upon approval from the FDA, we can further develop our device and begin to market, while also assuring that we are prepared for a spontaneous FDA quality system inspection any time after 510(k) clearance.[23]

Ethics

This design took into account various ethical considerations in accordance with the BMES Code of Ethics. The design enhances the welfare of the public by increasing the independence of those with limited dexterity. However, the design is not limited to users with limited dexterity. This technology will be available to anyone who wishes to use it. The device could also be implemented with art utensils other than just paint brushes. When testing the design, careful considerations were made and will be made to ensure humans are rarely involved and animals are not involved. If humans are needed for the testing of the device, surveys are usually implemented and safety is the main priority. Accurates results of testing were presented throughout and will be with any further testing. Any findings from testing are used to improve the design of the device. These ethical considerations conform to professional, health care, and research obligations of practicing engineers.

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Appendix A: Target Value Justifications

Justifications for Constraints

- **Safety:** The product must not have sharp edges that could cut the user with regular use. In order to measure the sharpness of the device, we considered a BESS Scale (see **Figure 8**), where any value over 400 can be deemed non-sharp**.** This scale was chosen due to its ability to accurately measure edge sharpness.[7] The metric of 400 or above was chosen because it represents dulled, non-sharp edges. The other target safety value is a pass/fail for the use of latex, acrylics, and formaldehydes, as they are common allergens.[8]

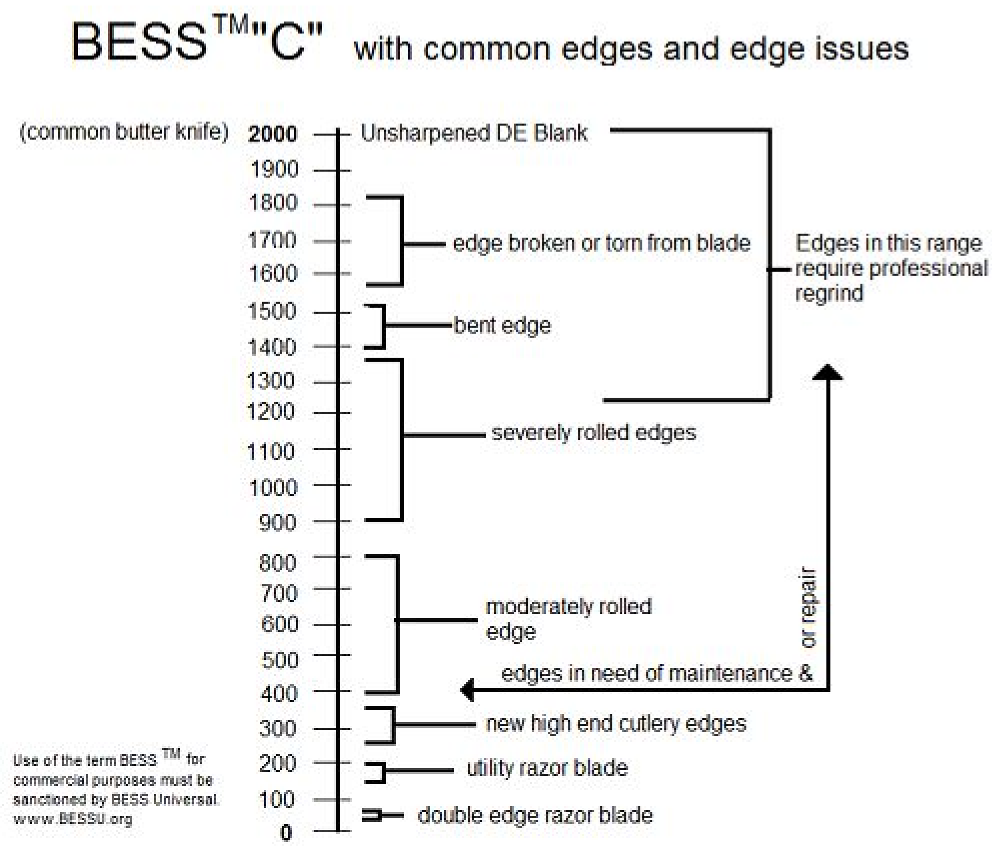

Figure 8: BESS scale for sharpness. Each number on the edge scale corresponds with the nm edge apex radius. For example, a score of 50 on the BESS scale approximates to a 50 nm edge apex radius, which can also be described as a 0.1 micron edge apex width. [7]

- **Compatibility**: The product must be able to fit a variety of different paint brush sizes. The target values of <12” in length and <1.5” in width were obtained using the benchmarked product of a Flat Wide 1 Inch Paint Brush,[11] which we considered as the largest size that an artistic paintbrush would be. The target values for length and breadth of the device were determined based on the average range of hand sizes across kids and adults.[9] Essentially, the product should be able to be used by people of all ages and compatible with various hand sizes.
- **Adjustability:** The target values for extension, flexion, radial, and ulnar angles were chosen based on the average range of motion of the wrist (see **Figure 9**).[11] Within each design, the paintbrush should move in coordination with the wrist, allowing for a wider range of motion while painting. The lock on the device should be able to withstand the force exerted by the user while painting without having the brush fall out of place. The lock on the product is an active lock that can be easily adjusted by the user. [12] This will be tested using a pass/fail mechanism.

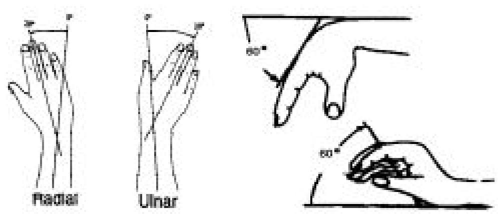

Figure 9: 20° radial and ulnar movement of wrist, and 60° wrist flexion and extension, respectively shown.

Justifications for Wants

1. **Low Cost of Production:** The target value of $50 was benchmarked based on the amount of value that the product rewards the user. Since our product is subject to several wants and constraints, the user knows they are getting the maximum value for their investment. Similar benchmarked products have a market price ranging from $20-$30, but these products do not return the user with the same quality and value, as they fail to uphold certain wants and constraints of the user.[4]–[6] Based on the market value of similar products, specifically the "Sammons Preston T-Bar Holder", the benchmark of $50 was placed since this device is of higher quality.

2. **Lightweight:** The product must be lightweight and easy to carry for the artist. The target value of <8 oz. was derived from average paint brush weight, and increased slightly to accommodate for an increase in the device's weight to allow for other constraints to be met. [10]

3. **Portability:** The target value was benchmarked based on the size of similar existing products.[4]–[6] All benchmarked products were less than a foot in total length and were able to be transportable due to their convenient size. This product must also be of convenient size, as any product over a foot's length would be difficult to fit into a pocket or purse.

4. **Durability/Reusable:** The product should be able to resist deformation following repeated use. The target value of 250 kPa is benchmarked based off of the average stress generated by the hand when gripping power tools.[24] Since users grip power tools with much force, this benchmark is a good testing value for the amount of maximum stress a user would exert on the product. The product will be tested under 250 kPa of stress 52 times, since the intended use is once a week and the product is expected to last one year without workmanship/material defect. The measure of 250 kPa should fall within the elastic deformation portion of the material's stress/strain curve, since the elastic region is where a material will not permanently deform when stress is applied.[14] By having the product be durable over a one year period, this assures that the product is reusable, which is friendly for the environment. Given that most plastics are not biodegradable, having a product being reused several times and recycled at the end of its life generates a great impact on the environment.

5. **Easily Found Replacement Parts:** The target value of being able to be purchased on Amazon means that the product can be easily accessed by any user globally. Following purchase, the assembly of the product should not require much processing, meaning most fixes can be made using household tools such as a hot glue gun, and don't require much

machinery. According to the Engineering Design Handbook, this strategy is what makes the product maintainable over a long period of time.[15]

6. **Easy to Use:** Product should be easy to use with answers greater than 4 for each of the statements in the "Ease of Use Survey" located below. If the user "strongly agrees" or "somewhat agrees" to each of the statements, this entails that the product is user-friendly and the majority of users have similar experiences while using the product. Survey is a simplified user feedback mechanism adapted from the USE Questionnaire for Reliability and Validity.[16] See **Appendix C.1.**

7. **Easy to Clean:** The product should be paint-free, with a score less than 2 on the "Visibility Scale" after a thorough cleaning to ensure reusability and aesthetics. In accordance with ASTM D5913-96 standards, the cleanliness of a paintbrush is tested using a visual scale, measuring the amount of paint residue left on the brush. [17] This product establishes its own visibility scale, added onto the end of use survey. See **Table 4** in **Appendix C.2.**

8. **Aesthetically Pleasing:** The product should be culturally accepted and vibrant, meaning that it is colorful and appeals to the eye of all ages, with answers greater than 4 for each of the statements in the "Aesthetics Survey" located below. If the user "strongly agrees" or "somewhat agrees" to each of the statements, this entails that the product is aesthetically and sensory appealing and the majority of users have similar experiences while using the product. Survey is a simplified user feedback mechanism adapted from the USE Questionnaire for Reliability and Validity. [16] See **Appendix C.3.**

Appendix B: Engineering Standard Justification

The adaptive paintbrush is a device that must be safe and compatible for use of those with physical and mental impairments. It is critical that the device must be of appropriate size, material selection, and reusability.

ASTM D5301-92 provides information about common brush types, including dimensions and materials.[25] This will be helpful if our design incorporates a device that will be used alongside already existing paint brushes. For example, if the paint brush inserts into a part on the device, this standard will be helpful in determining how large that insert needs to be and the range of its adjustability for different types of brushes. This standard will also be a good resource to direct our research by using the proper terminology required for specific information regarding the brush.

ASTM D5913-96 provides a test method to measure the cleanability of paint brushes.[17] The adjustable paint brush is intended to be reusable, therefore proper measures must be taken to assure the paint brush can be cleaned following use. Utilizing the standard in the project will help our group select the best brush bristle material to fit our needs.

ASTM F624-09 analyzes the different polyurethane solids and their use in biomedical applications.[26] The adjustable paintbrush is expected to incorporate memory foam (low-resilience polyurethane foam) for more user comfort. Within the standard, detailed procedures are listed for testing of this polyurethane foam for properties such as tensile strength, creep, flexural strength, and water absorption. All are properties that should be considered within our design to fit the users needs.

Appendix C: Patient Satisfaction Surveys and Visibility Scale

1. ***Ease of Use Survey***

   Please indicate how much you agree with the following statements:
   - I feel comfortable using this product.
   - This product is easier to use than previous solutions I have tried.
   - I feel little to no difficulty using the product.
   - This product makes me feel more independent while painting.
   - This product is easy to carry around with me.
   - I would rather use this compared to previous solutions.
   - It was easy to travel with this product.

   Use the following scale to indicate your level of agreement:
   1. Completely Disagree
   2. Somewhat Disagree
   3. Neutral
   4. Somewhat Agree
   5. Completely Agree

   Score on the survey is taken as the average score (1-5) for each statement.

2. ***Visibility Scale***

   Table 4: Visibility scale, adapted from ASTM standard D5913-96, to test the "easy to clean" metric. [17]

Rank	Description
1	No paint visible
2	Specs of paint visible
3	50% of paint present prior to cleaning is visible
4	Most of all paint present prior to cleaning is visible
5	All paint present prior to cleaning is

3. ***Aesthetics Survey***

   Please indicate how much you agree with the following statements:
   - The product is colorful.
   - The product is clean looking.
   - The product has a creative visual design.
   - The product is visually stimulating.
   - The product is pleasing to look at.

Use the following scale to indicate your level of agreement:

1. Completely Disagree
2. Somewhat Disagree
3. Neutral
4. Somewhat Agree
5. Completely Agree

Score on the survey is taken as the average score (1-5) for each statement.

Appendix D: Weighted Decision Matrix

Table 5. Weighted decision matrix for three preliminary concepts. Constraints were not evaluated since they were required for the design.

Evaluation Criteria	**Weight**	**Max**	**Flexible Grip**		**Roller Hand Brace**		**Ball-and-Socket**	
			Score	Weighted	Score	Weighted	Score	Weighted
Low Cost of Production	.2	10	10	2	7	1.4	8	1.6
Lightweight	.17	10	8	1.36	5	.85	4	.68
Portability	.15	10	10	1.5	9	1.35	9	1.35
Durability	.15	10	6	0.9	8	1.2	7	1.05
Easily found replacement parts	.12	10	7	0.84	10	1.2	5	0.6
Easy to use	.12	10	8	0.96	7	.84	6	0.72
Easy to clean	.05	10	8	0.4	6	.3	10	0.5
Aesthetically and sensory pleasing	.04	10	10	0.4	7	.28	10	0.4
Total	1.0		8.36		6.22		6.9	

Appendix E: Technical Descriptions, Detailed Justifications, and Design Schematics

A. *Cross Hand Grip*

a. Technical Description

i. This component is made of armature wire inserted into Polylactic Acid (PLA) 3D filament. It is shaped as an "X" with each intersecting rectangle measuring 6.5" lengthwise and 2" wide. The entire component has a thickness of 0.1".

ii. The holes going through the material near the wrist end of the component have a diameter of 0.25" and are located 0.5" from each strap's internal edge. The elastic band running through these holes has a thickness of 0.2" and diameter of 1.8". The compressive mesh running along the bottom of the device on the end where the artist's fingers are is secured with epoxy adhesive along the outer edges.

b. Detailed Justification

i. The "X" shape was chosen to provide greater stability for the base of the overall design, allowing for a more sophisticated approach to the other components involved in the design. This shape, with its increased surface area, also allows for much greater independence, as it is more rigidly defined than a singular long, bendable piece of material that the artist would have to wrap around their hand on their own. More likely, an aid would end up putting that type of device on for the artist and we wanted to avoid that. Finally, the elastic band going through the device and around the artist's wrist, along with the mesh enclosing the fingers, allow for greater stability and security while using the device. Therefore, the artist will feel more confident and independent using the device.

ii. The materials of this component allow it to bend and retain its shape, while providing comfort and the surface area needed to support the rest of the device. The armature wire inside the PLA allows the material to be bent and maintain its position. The PLA filament 3D printed to surround the armature wire protects the user from any pinching or hardness they would otherwise feel. The soft PLA is extremely flexible and acts as rubber. The PLA allows for flexibility and is printed to the dimensions calculated below. Furthermore, PLA is composed of renewable resources and is completely biodegradable.[9]

iii. The material and size chosen for the elastic wrist band were based on the specifications of a standard hair tie. The ones we specifically chose to implement have a thickness of 0.2" and diameter of about 1.8".[29] These specifications were chosen because standard hair ties can often be found worn on people's wrists for an entire day or even longer without causing any discomfort. They can also be stretched and twisted around hair numerous times before becoming overly stretched or torn.

iv. The compressive mesh material providing support to the user's fingers was chosen based on its ability to provide support while also being lightweight. The polyester power mesh is typically used in clothing for control tops or other smoothing techniques.[27] This great compressive ability will help provide stability, confidence, and independence to the user.

v. The dimensions of this component were calculated based on the average hand sizes with average length of 4.4” - 7.6”. and average breadth of 2.0” - 3.5”.[10] The following calculations were performed to arrive at the dimensions of the “X” being used:
   1. assume the palm is approximately ½ the length of the entire hand
      a. max length: 7.6/2 = 3.8”
      b. length of diagonal:
         i. $(3.8^2 + 3.5^2) = 5.2$”.
      c. add 1” for wrapping around side of hand/error
         i. 5.2 + 1 = 6.2”.
         ii. round up to 6.5” (doesn’t hurt to have extra material)
      d. width of strap:
         i. min breadth = 2.0”.
         ii. min length = 4.4/2 = 2.2”.
         iii. area of min palm = 2*2.2 = 4.4 in^2
            1. overlap of straps should be no larger than 4 in^2
               a. each strap should be 2” wide

vi. The size of the holes for the wrist strap is based on the thickness of a standard elastic hair tie, which is similar to what we will be using. This average size is 5 mm or about 0.2”.[28] To allow for error and ease of putting a new wrist strap through the holes in case one breaks or gets worn out, the diameter of the hole measures 0.25”.

c. Detailed Design Schematic

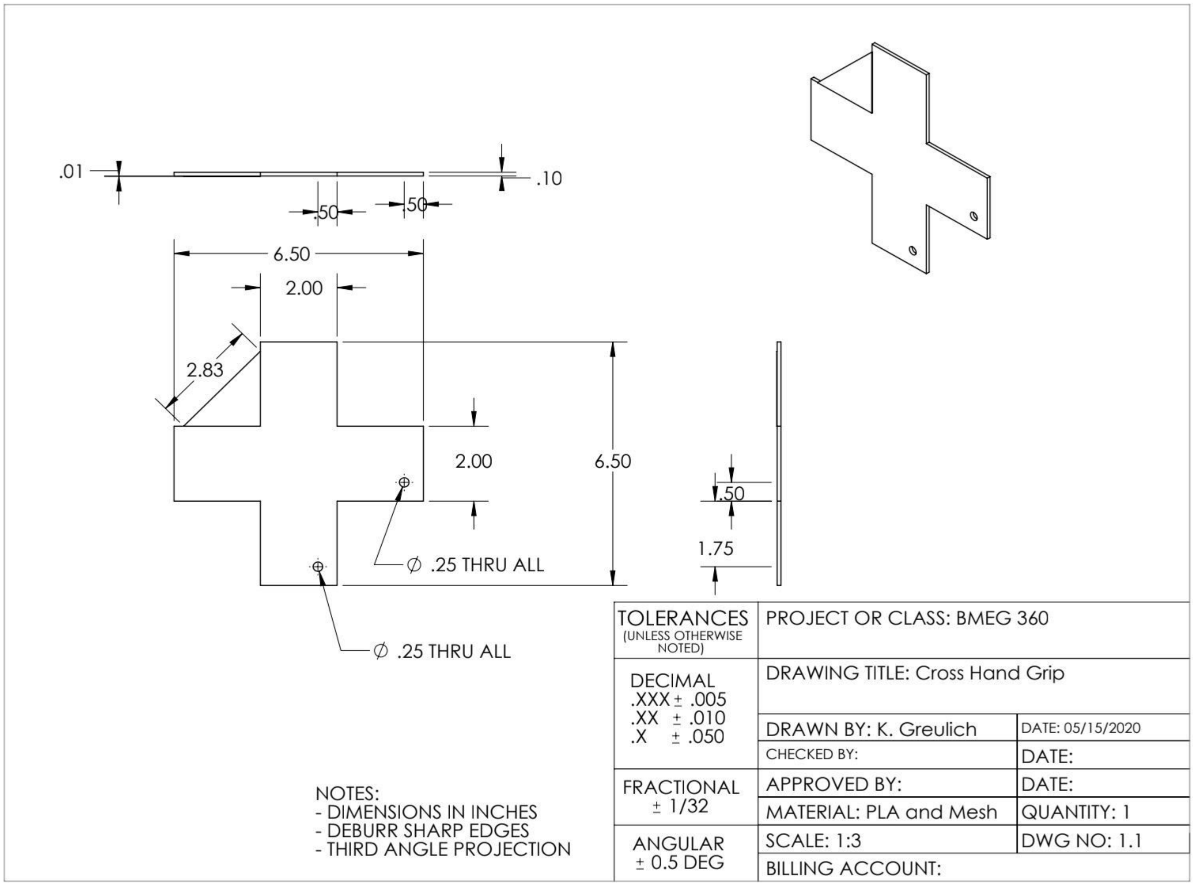

Figure 10: Solidworks drawing of cross hand grip. The elastic wrist band will be running through the holes pictured. The mesh will be attached with epoxy on the underside of the device, leaving a gap for the user to put their fingers through. The "X" will sit on the top of the hand so that the middle of the "X" is in the middle of the hand and the straps with holes will be running toward either side of the wrist, with each of the four straps wrapping around the hand.

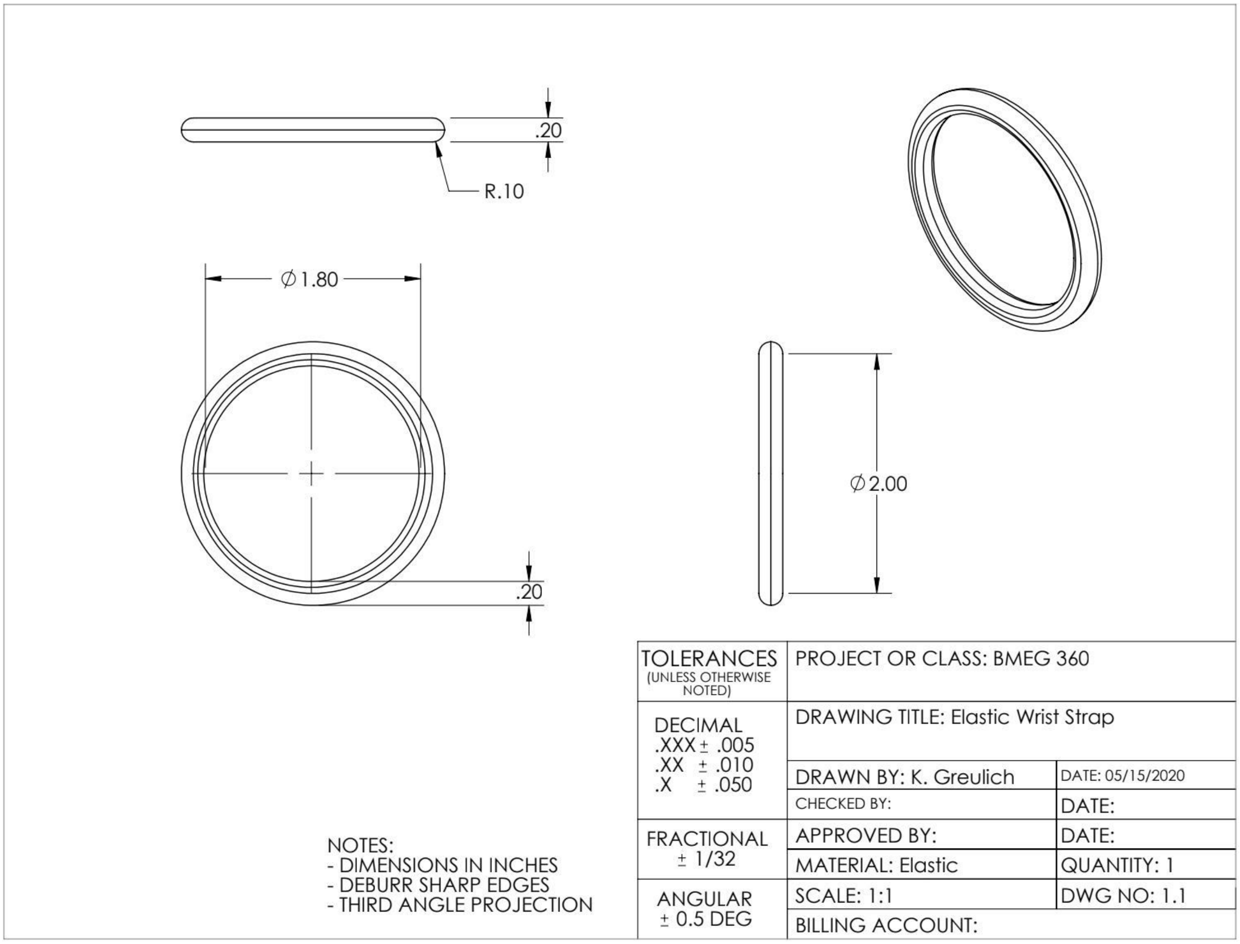

Figure 11: Solidworks drawing of elastic wrist strap. The strap will run through the holes of the cross hand grip shown in **Figure 10** and comfortably fit around the user's wrist.

B. Ball-and-Socket Joint

a. Technical Description

i. The joint (both the ball-and-socket base) is made of ABS plastic. The ball is a sphere with an inner radius of 0.80" and an outer radius of 0.90". It sits in a cylinder shaped socket, with a radius of 1.0" and height of 1.0".

ii. The inside of the ball contains two elliptical "axes," which attach to two servo-motors (See Component C and **Figure 13**). These axes have radii of 0.790" and 0.150" and a height of 0.60". On top of the ellipses are two cylindrical notches (inner radius of 0.094"). This is where the servo-motors attach.

iii. The ball will be attached to Component E, the brush holder, with an epoxy glue. This will allow for the brush position to be moved in any direction.

iv. The ball's movement is controlled via a joystick that the user controls with their non-painting hand. The joystick is connected to a circuit (Component

C), built with Arduino, that will allow for motor movement in the x- and y- directions.

b. Detailed Justification

i. The ball-and-socket joint was chosen because it allows for motion of the brush in any direction, therefore maximizing adjustability. This is preferable over a hinge joint in which motion is only available in one or two directions. We debated between the two, but ultimately decided the ball-and-socket provides more movement and would provide a more streamlined look.

ii. ABS plastic was chosen because it is easily 3D printed and will allow for seamless integration with Component E.

iii. The size of the socket, with a 2.0" diameter, was chosen based on average hand size.[9] Average hand breadth is between 2.0"-3.5". Therefore, 2" will not exceed the size of the hand and will also fit firmly on top of the base, Component A.

iv. The ball also needs to be big enough to fit the two servo motors that control its movement. The chosen servo motors are approximately 0.85" x 0.89" x 0.46" in size. Therefore they are small enough to fit into a ball with a 0.80" radius. Additionally, the two motors will have a volume of 0.70 in^3. A ball with an inner radius of 0.80" radius has a volume of 2.14 in^3 of empty space. This is more than enough volume to fit the servo motors.

v. ABS plastic has a density of 1.1g/cm^3 (0.636 oz/in^3). A hollow ball of these dimensions has a volume of 0.909in^3. Each ellipse has an area of 0.372in^2, and a height of 0.06". Therefore the total volume of both ellipses is 0.044in^3. This, combined with the hollow ball, corresponds to a weight of 0.606 oz. This is less than an ounce, meaning it is very lightweight and an appropriate size.

vi. Originally, a keypad was chosen to control the joint as opposed to a joystick. However, a joystick is a much feasible control to design in Arduino, and provides a similar amount of independence to the artist.

c. Detailed Design Schematic

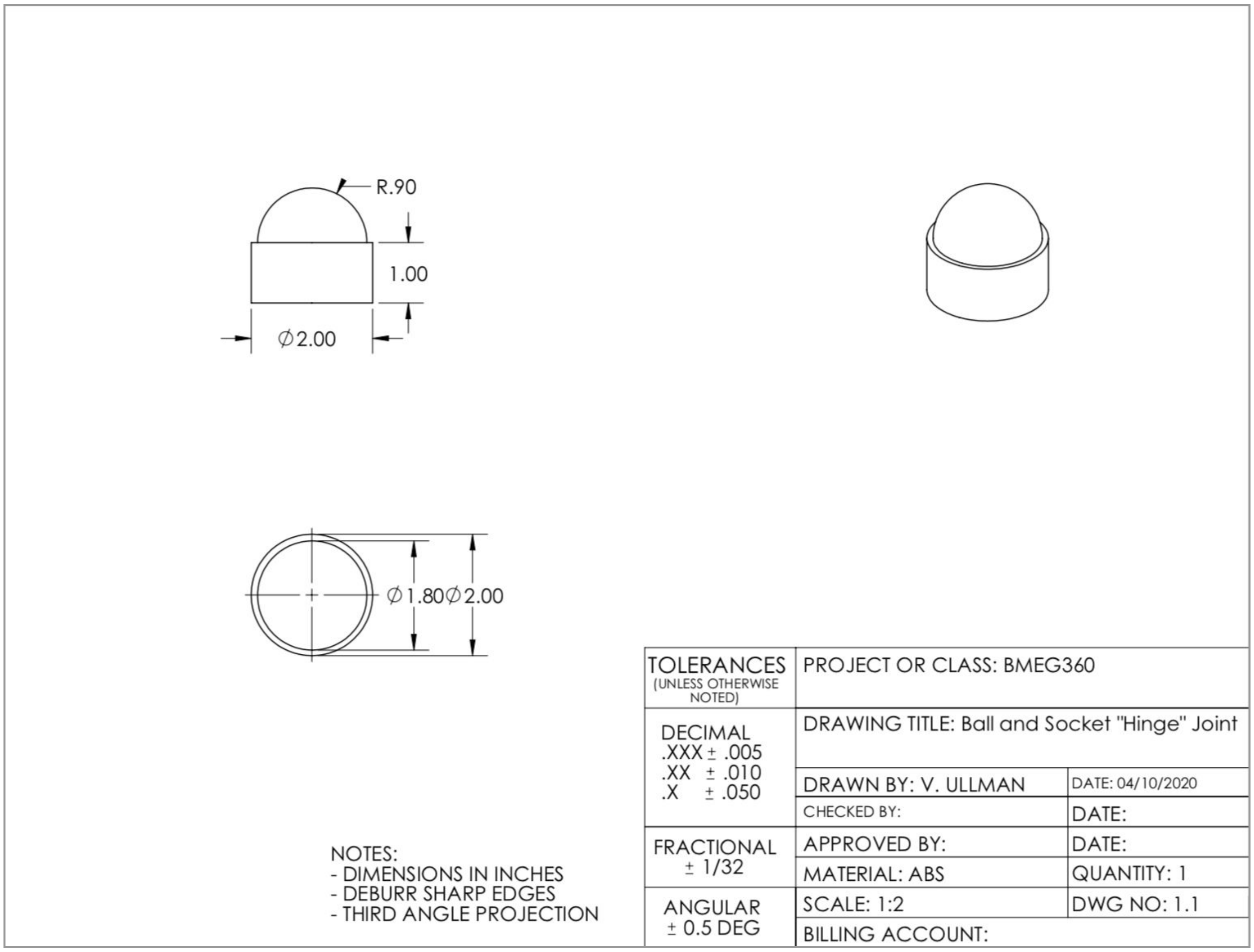

Figure 12: Detailed engineering drawing of ball-and-socket joint. The ball has a radius of 0.90" and sits in a cylindrical socket with a radius of 1.00" and a height of 2". This socket sits atop the cross hand grip shown in **Figure 10.**

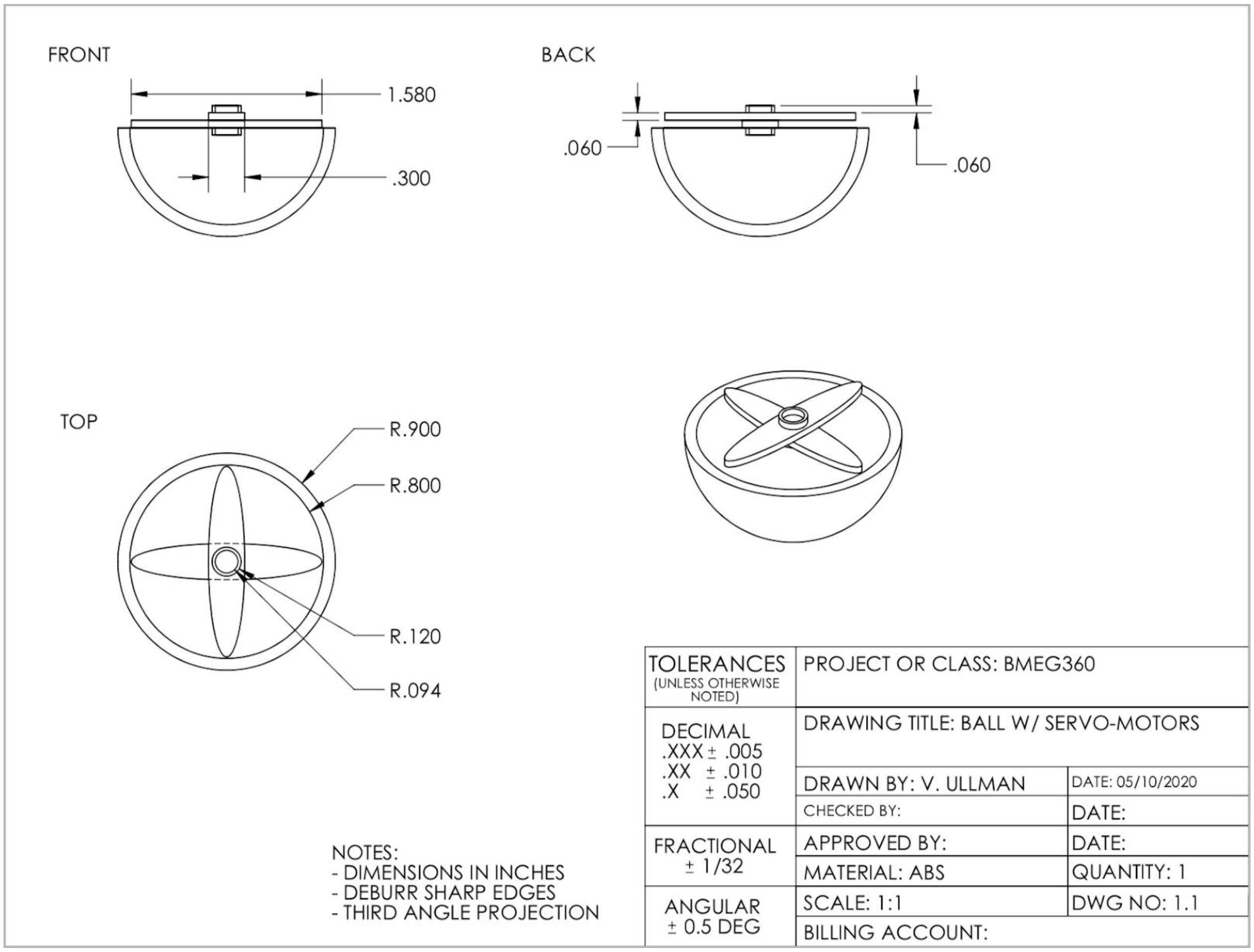

Figure 13: Detailed engineering drawing of the inside of the ball-and-socket joint. This ball has two axes built into it, made of ellipses with radii of 0.790" and 0.150", and a height of 0.06". These ellipses contain two circular notches, where the servo-motors for the joystick control will attach.

C. *Circuitry to Control Ball-and-Socket*

a. Technical Description

i. The circuit, built with Arduino, controls the movement of two servo motors. These servo motors are oriented in opposite directions, and sit inside the "ball" of Component B. Each motor corresponds to movement along an axis, allowing the brush to move from side to side, and up and down. The two servo motors are connected to the arduino circuit and controlled by the joystick, which will be moved by the artist's free hand.

ii. The specific joystick model used will be the "5Pcs PS2 Game Joystick Switch Sensor Module Geekcreit for Arduino" from GeekCreit.[29]

iii. The Arduino board is the "UNO R3 ATmega16U2 AVR USB Development Main Board Geekcreit for Arduino," also from Geekcreit.[30]

iv. The two servo motors are the “SG90 9g Micro Servos for RC Robot Helicopter Airplane Controls Car Boat, ” from Deegoo and available on Amazon.[31]

b. Detailed Justification

i. Arduino was chosen because it is easy to use for projects such as this one. There are thousands of Arduino projects available online, which made it easy to find models and examples to follow. It also simplifies the electronics so that ATE patients and workers could understand it easier, despite the lack of an electrical engineering background.

ii. The circuit uses a joystick as opposed to button controls, because it is a more widely used controller in Arduino circuits and has been proven to work for other Arduino users. Additionally, it is easier to grip and control, since the user can wrap their hand around the joystick.

iii. The joystick still offers the user a wide range of motion of the brush and is relatively easy to control.

iv. The chosen servo-motors have a maximum torque of 1.8kg/cm (161.3oz/in). The servo-motors’ elliptical axes are working from a distance of 0.79” (the length of the longer radius). This means the servo-motors can each move a maximum weight of 127.4oz. This well exceeds the overall weight of our entire device, which means the servo-motors are definitely strong enough to control movement of our design.

v. Since the servo-motors physically attach to the ball, they control the movement of the ball and prevent any slipping.

c. Detailed Design Schematic

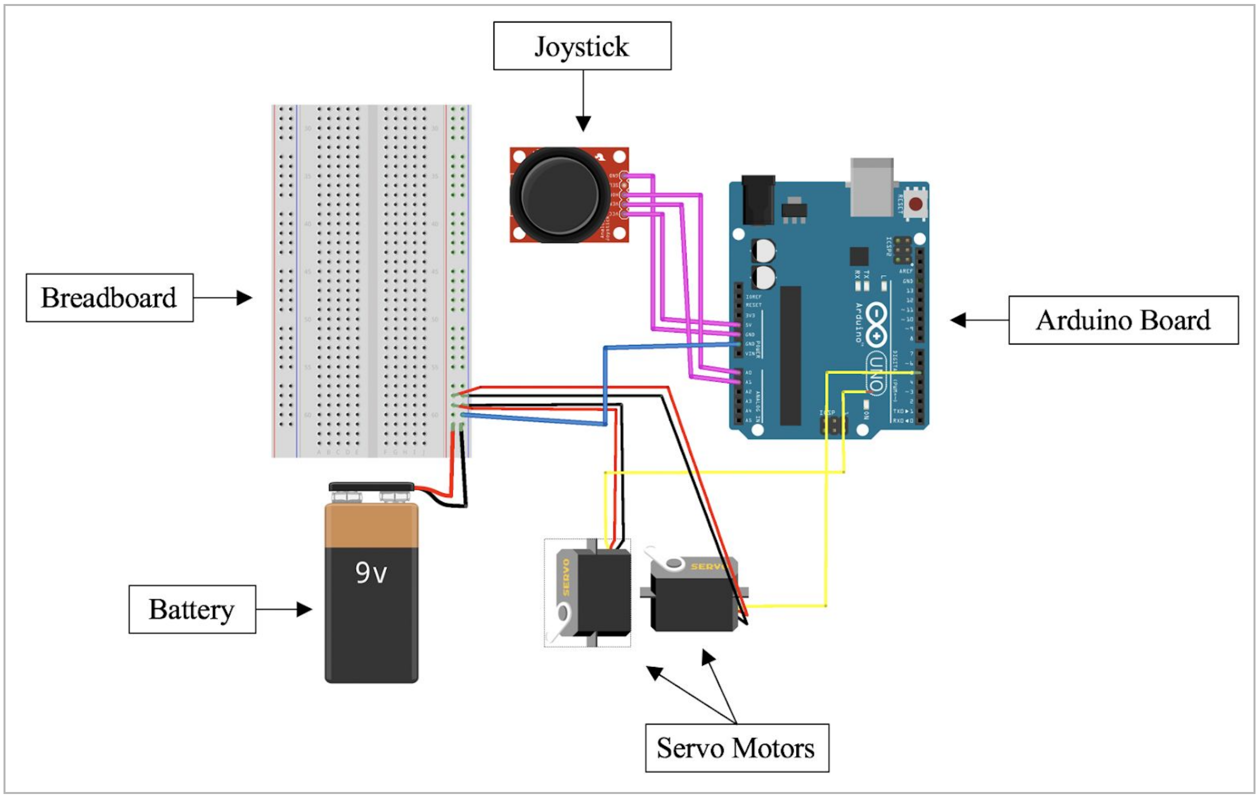

Figure 14: Fritzing diagram depicting the Arduino circuit used to control the servo-motor position. Joystick connections are shown in pink, while servo-motor connections are shown in yellow.

D. Joystick

a. Technical Description

i. Controlled by the user's non-painting hand. It sits grounded to a surface.

ii. User places palm

iii. Base is 2" x 2" x 0.5", which is small enough to be portable with the device itself.

iv. Ball portion of joystick is spherical with a diameter of 1.54"

v. Made of an ABS plastic coating atop of a standard arduino joystick.

b. Detailed Justifications

i. Size of the sphere was chosen to be large due to the artist's limited dexterity. With a diameter of 1.54", the artist can grip the joystick using their palm rather than having to use their fingertips. With the original Arduino joystick, the user would have to grip a joystick that measures 26 mm (1.03”) in diameter. In effort to increase independence, this larger sized joystick was chosen.

ii. Size of the base was chosen as 2” x 2” x 0.5” to accommodate the circuitry and original Arduino joystick.

iii. ABS was chosen as the coating of the joystick due to its softness to touch, as well as its ability to be 3D printed. Other materials such as rubber and PLA were considered, yet the bulk of our device uses ABS which has proven to be a strong and durable plastic, as well as being smooth to touch and easy to clean.

c. **Detailed Design Schematic**

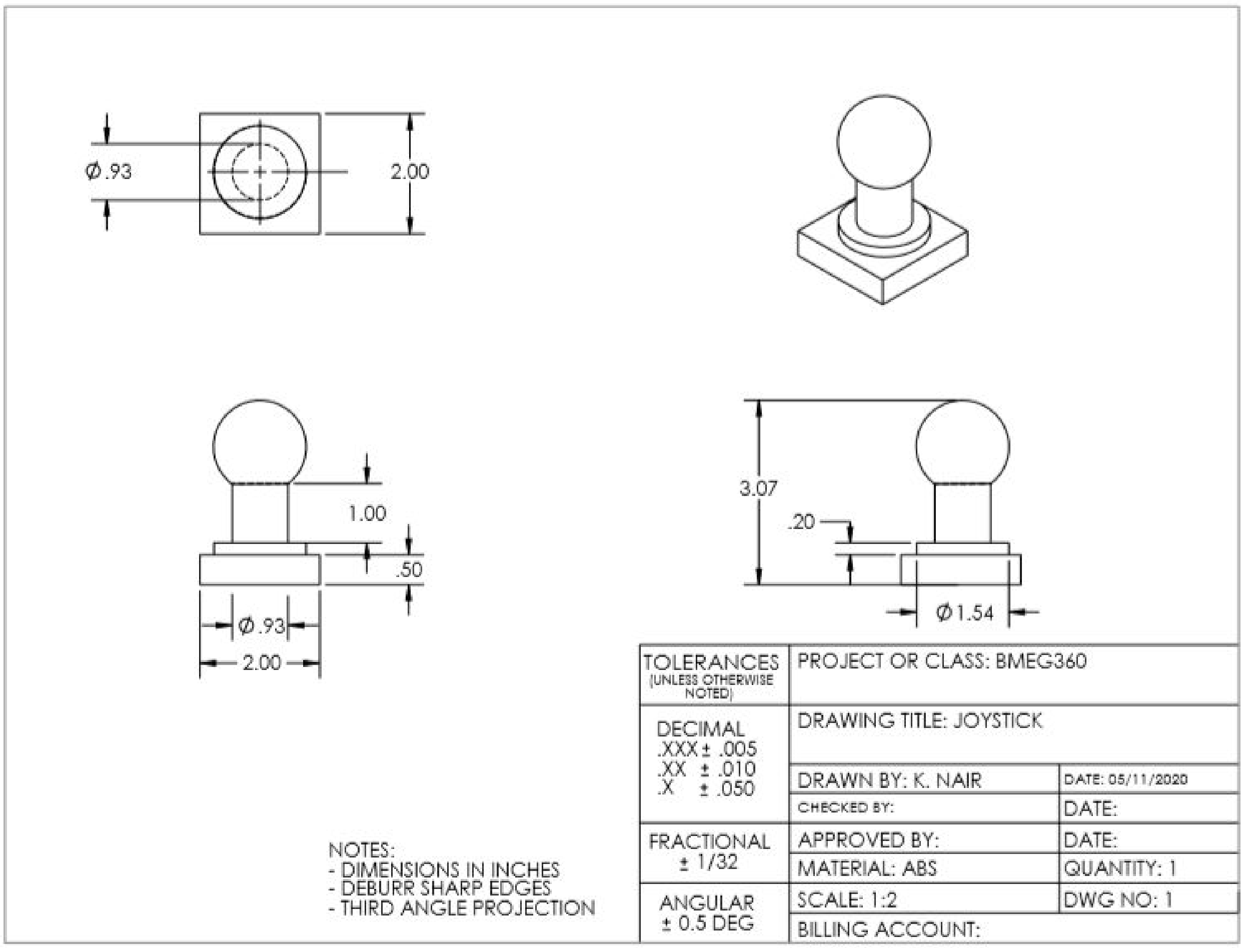

Figure 15: Engineering drawing of joystick. User places palm on the ball of the joystick to manipulate the movement of the joystick.

E. Cylindrical Brush Holder

a. Technical Description

i. Device is made of a ABS Plastic hollow cylinder as the base, with an internal stainless steel locking mechanism. The cylinder measures 2” in length with an outer radius of 0.5” and inner radius of 0.35”. The lock consists of a button of 0.18” radius, and a latch of length 0.5”, as well as an extrusion of radius 0.18”on the opposing side of the latch (see **Figure 16**). The lock lies 0.53” from the top of the cylinder, and 0.94” from the bottom of the cylinder. The referenced push button is “Push Button Switch Latch Replacement For Boat Door Glovebox Southco 93-30”.[20] The cylinder can be 3D printed, with the stainless steel locking mechanism to be attached using an epoxy glue.

ii. To use this device, the user inserts the paintbrush handle at the top of the cylinder and places it at a desired location length. This desired length varies with different uses and is based on how close the user keeps their hand to the Canvas (see **Figure 15**). Once the brush handle is comfortably positioned into the holder, the user then pushes the button to lock the brush into place by pushing a latch against the handle and securing it between the latch and the extrusion. When the user is finished painting or wants to change the brush, they simply push the button again and the latch releases, allowing the user to remove the brush from the holder.

b. Detailed Justification

i. The button was chosen to give the user an increased sense of independence. The alternative would have been to have the user manually tighten the brush into place with a velcro strap, yet with this modification, the user simply has to push a button and the brush is secured into place. This choice is slightly costlier, with the button costing $5.99[20] and the strap costing $1.00,[32] yet the benefit with regards to independence outweighs this cost. The button is positioned 0.53” from the top of the cylinder to assure that the paintbrush is stable and balanced while in the cylinder. A mechanical latching button was chosen over an electronic button due to simplicity of the lock. An electronic lock would garner more wiring and circuitry which are overly complex for this design.

ii. A stainless steel locking mechanism was chosen since that is a benchmark material for similar push button latching locks.[20] ABS was chosen as the outer base since it is a common 3D printed metal and can also create a strong bond with stainless steel when exposed to epoxy glue.[18] ABS plastic is also easy to clean if exposed to paint and durable under high loads. Other materials such as stainless steel and other metals were considered but ultimately forgone due to the want for keeping the product lightweight.

iii. The length of the cylinder, 2.0”, was determined based on the average height of the dorsal side of the hand, between the wrist and knuckles.[9] An inner radius of 0.35” was chosen to accomodate for multiple brush sizes. The largest benchmarked brush size handle was 0.39” in diameter.[10] The structure is designed to fit all brush sizes up to 0.50”. The latch is designed to move to secure differing handle sizes accordingly, allowing for increased compatibility as defined in the constraints.

c. Detailed Design Schematic

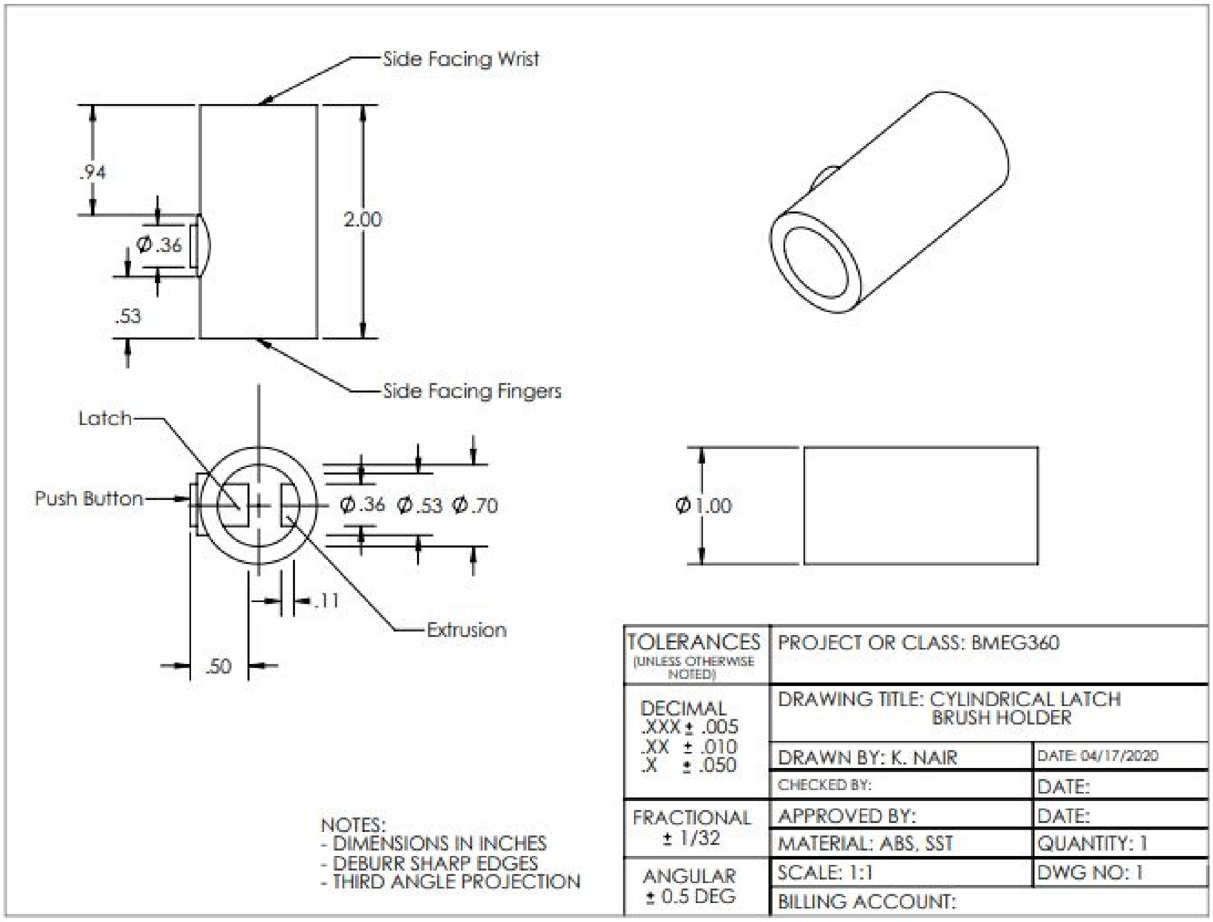

Figure 16: Engineering drawing of cylindrical brush holder. Brush inserts into the side facing fingers and is secured by push. Latch pushes against the brush handle and locks it against the extrusion.

Appendix F: Arduino Code for Component C*

```
//add the servo libary
#include <Servo.h>

//define our servos
Servo servo1;
Servo servo2;

//define joystick pins (Analog)
int joyX = 0;
int joyY = 1;

//variable to read the values from the analog pins
int joyVal;
void setup ()
{
  //attaches our servos on pins PWM 3-5
  servo1.attach(3);
  servo2.attach(5);
}

void loop ()
{
  //read the value of joystick (betwen 0-1023)
  joyVal = analogRead(joyX);
  joyVal = map(joyVal, 0, 1023, 0, 180); //servo value betven
0-180
  servo1.write(joyVal); //set the servo position acording to the
joystick value

  joyVal = analogRead(joyY);
  joyVal = map (joyVal, 0, 1023, 0, 180);
  servo2.write(joyVal);
  delay(15);
}
```

Appendix G: Anticipated Cost

Table 6. Final Design Anticipated Cost (See Appendix H for Calculations*)

Vendor	Company	Reference	Description	Item Number /SKU/ASIN	Qty	Price per part	Total
Amazon	Overture	[33]	1.75 mm PLA 3D Filament (332 m spool)	B07PGY2JP1	1/22	$24.99	$1.17*
Amazon	Jack Richeson	[34]	1/16 in. Armature Wire (2 32' spools)	B01B0Y06SA	3/64	$11.49	$0.54
Amazon	Goody Ouchless	[35]	4mm Elastic Band (27 count)	B00DFSHD5O	1/27	$4.11	$0.16
Mood Designer Fabrics	Mood Designer Fabrics	[27]	Black Stretch Polyester Mesh	306806	1/6	$6.99/yd	$1.17
Amazon	Gorilla	[36]	Epoxy Adhesive (0.85 oz)	B001Z3C3AG	1	$5.47	$5.47
Banggood	Southco	[20]	Push-Button Switch Latch	1574777	1	$5.99	$5.99
Banggood	Geekcreit	[22]	Joystick Controller	76465	1	$1.55	$1.55
Banggood	Geekcreit	[30]	Arduino Board	68537	1	$9.17	$9.17
Banggood	Banggood	[37]	Circuit Breadboard	91872	1	$4.07	$4.07
Banggood	Banggood	[38]	Jumper Cable Wires (40pcs)	994061	7/40	$2.61	$0.46
Amazon	Deegoo	[31]	Servo Motors (4pcs)	B07MLR1498	2/4	$8.98	$4.49
Amazon	AmazonBasics	[39]	Battery (8pcs)	B00MH4QM1S	1/7	$10.99	$1.37
Amazon	Octave	[40]	ABS 3D Printer Filament*	B0083HSPH2	1/23	$21.95	$0.95*
						Total	$43.10

Appendix H: Cost Calculations

Calculations for ABS 3D Printing Filament:

- Filament Length = 400 m, Diameter = 1.75mm, meaning 1.1 m^3 = 43.3 in^3 of material
- Amount needed for holder: .362 in^3
  - External Surface + Extrusion
  - $(.5-.35)^{\wedge}2*\pi*2 + (.265^{\wedge}2)*\pi*1 = .362\ in^3$
- Amount needed for ball-and-socket: 1.5 in^3
  - Sphere + Cylinder
  - $(4/3)*\pi*(.9^3-.8^3) + (\pi*(1^2-.9^2)*1) = 1.5\ in^3$
- .362+1.5 = 1.862 in^3 total ABS needed
- **Unit Cost** = (1.862/43.3)*21.95 = $0.95

Calculations for PLA 3D Printing Filament:

- Amount needed for Cross Hand Grip:
  - middle square: 2*2*.1 = 0.4 in^3
  - straps coming off middle: 2.25*2*0.1 = 0.45 in^3
    - 4 straps: 0.45*4 = 1.8 in^3
  - Total: 0.4 + 1.8 = 2.2 in^3
- Filament Length Included: 332 m, diameter of 1.75 mm
  - 47.26 in^3
- **Unit Cost** = (2.2/47.26)*24.99 = $1.17

Appendix I: Verification & Validation Tests

Testing Protocol for Sharpness

Purpose: The purpose of this test is to determine the sharpness of the device. It was adapted from engineering standard UL 1439. [41] This standard aimed to prevent edges from causing cut type injuries during normal use, by using a sharp edge testing machine.

Procedure:

1. Gather the proper equipment needed for testing: A Sharp Edge-On-Up Professional Edge Tester (see **Figure 17**). For a detailed visual explanation on how to use the testing apparatus, please refer to the ShapeningSupplies website. [42]

Figure 17: Visual of testing apparatus. After zeroing device, insert edge onto chrome colored portion and record result.

2. Place each edge of the device on the apparatus and record the output.

Results: The test results look to analyze the sharpness of the device. According to the sharpness scale (see **Figure 8**), any reading over 400 refers to rolled edges, meaning they are not sharp to the touch. Since we do not have a physical prototype, we are unable to test the sharpness of the device, yet we can conclude that the sharpness of each edge on the device will be greater than 400 on this scale.

Testing Protocol for Allergens

Purpose: The purpose of this test is to determine whether the product was produced using any of the common allergens listed in the metrics table: latex, acrylics, and formaldehyde. This protocol was not adapted from any previous works.

Procedure:

1. Obtain product material list.
2. Pass/fail whether product contains latex, acrylics, or formaldehyde.

Results: Although we don't have a physical prototype, we do know of the materials that are going into our product. A material analysis was performed (see **Table 7**) and the conclusion was drawn that the product does not contain any common allergens.

Table 7. Material analysis to determine whether a product contains either of the common allergens.

	Does Not Contain:		
Material	**Latex**	**Acrylics**	**Formaldehydes**
PLA Plastic Filament	Pass	Pass	Pass
ABS Plastic Filament	Pass	Pass	Pass
Epoxy Glue	Pass	Pass	Pass
Armature Wire	Pass	Pass	Pass
Stainless Steel	Pass	Pass	Pass
Polyester	Pass	Pass	Pass
Circuitry	Pass	Pass	Pass

Testing Protocol for Compatibility of Different Users

Purpose: The purpose of this test is to determine whether the device can fit on hands of various sizes with dimensions taken from our metrics table of lengths from 4.4 - 7.6 in. and breadths of 2 - 3.5 in.

Procedure:

1. Obtain the device.
2. To allow for testing of the elastic wrist band in the fitting, expand the length by 1” so the maximum length is 8.6” and minimum is 5.4”.
3. Cut one block of wood to the maximum hand dimensions of 8.6” x 3.5” x 1”
4. Cut another block of wood to the minimum hand dimensions of 5.4” x 2” x 1”
5. Place device on block representing minimum hand dimensions with elastic band around one end, “X” straps around sides of the wood where the palm would be, and mesh around area where the fingers would be.
6. Observe and record whether the device fits with respect to mesh, straps, and wrist straps. If it does not fit in any one part, it fails. If it fits everywhere, it passes.
7. Repeat Step 5 and 6 on block representing maximum hand dimensions.

Results: Although we do not have a physical prototype of the device, we know that the dimensions of the device were designed around these different hand sizes and should pass this test (see **Table 8**).

Table 8. Pass/Fail Results of fit testing for different parts of device as well as the device as a whole.

Size	Wrist Band	Straps	Mesh	Whole Device
Minimum Dimensions	Pass	Pass	Pass	Pass
Maximum Dimensions	Pass	Pass	Pass	Pass

Testing Protocol for Fitting Various Brush Sizes and Lock Security

Purpose: The purpose of this test is to determine the effectiveness of the locking mechanism attached to the cylindrical brush holder. This protocol was not adapted from any outside source.

Procedure: 50 paintbrushes will be tested, with 5 types of paintbrushes of differing handle parameters including diameters and width. Of the 50 paintbrushes, there will be:

- 10 Santa Fe Art Supply 2 Inch Flat Brushes [43]
- 10 Santa Fe Art Supply ¾ Inch Flat Wide Brushes [44]
- 10 Santa Fe Art Supply Filbert Size 12 Paintbrushes [45]
- 10 Santa Fe Art Supply Filbert Size 10 Paintbrushes [46]
- 10 Santa Fe Art Supply Filbert Size 2 Paintbrushes [47]

This assures for a variety of different brushes to be tested, not just circular handle ones (see **Figure 18**).

1) Scatter the 50 brushes at random, and then one by one inserted into the cylindrical brush holder.
2) While in the holder, manually shake the device for 10 seconds in both the x and y direction (see **Figure 19)**. Record whether the brush stays in place or not (pass/fail).
3) During testing, record any observations, such as if the button is loose or hard to press.
4) With the data, create two graphs. One is a line graph of the total system, plotting whether the brushes passed or failed the test over the 50 intervals. This graph is independent of the brush type and looks to analyze the strength of the device itself, since it was designed to fit all brush sizes. Next, create a bar graph with 5 independent variables, one for each brush type, and have the success ratio (# of successful passed attempts/10) as the dependent variable. This data will help to analyze whether any specific brush type is not secured as well as the others, and how we can improve upon the design to assure better security.

Figure 18: Images of Santa Fe brushes that will be tested. 1a corresponds with the 2” Flat brush, 1b with the ¾” Flat Wide Brush, 1c with the Filbert Size 12 brush, 1d with the Filbert Size 10 brush, and 1e with the Filbert Size 2 brush.

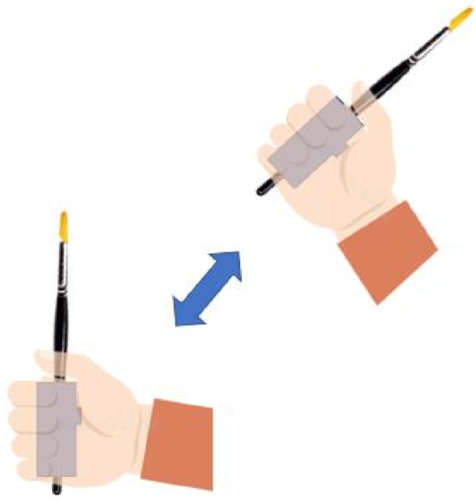

Figure 19: Diagram of shaking motion for testing. This motion is continued for 10 seconds for each brush.

Results: The test results look to analyze the overall viability of the device, as well as the compatibility with different sized brushes. Unfortunately, since we do not have a physical component of this device, we cannot officially test it using this protocol. The ideal results should reflect that there are some failures with the lock with greater iterations, due to greater use (see **Figure 20**). In addition, there should be some failure with the 2” Flat brush and the Filbert Size 2 brush, since these are extreme highs and lows for brush sizes (see **Table 9 and Figure 21**). The test results should look something like the following:

Table 9: Success ratio of different brushes. Total success ratio is 45/50 with failure occurring at the 32nd, 36th, 40th, 42nd, and 49th brush.

Brush Type	**2” Flat**	**¾” Flat**	**Filbert 12**	**Filbert 10**	**Filbert 2**
Success Ratio	.8	1	.9	1	.8

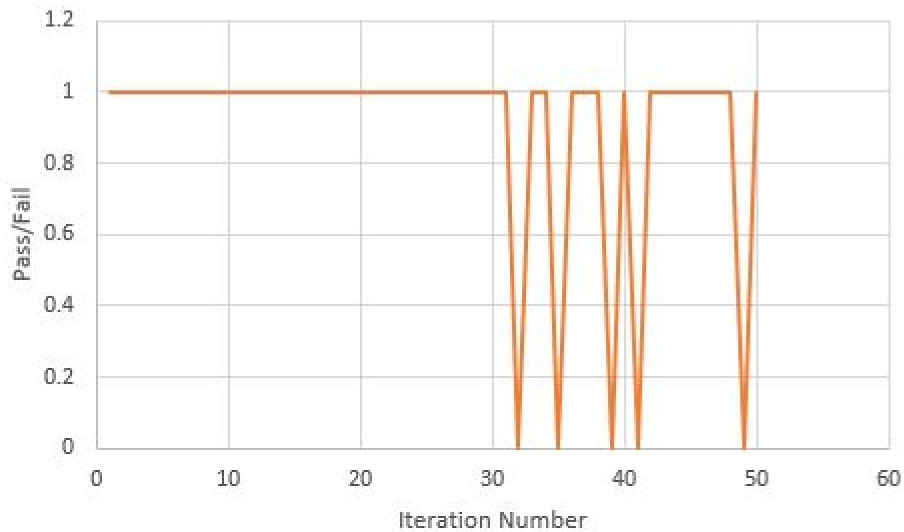

Figure 20: Pass/Fail data over 50 iterations. Value of 1 corresponds with pass, value of 0 corresponds with failure. Trend shows failure with increased iterations.

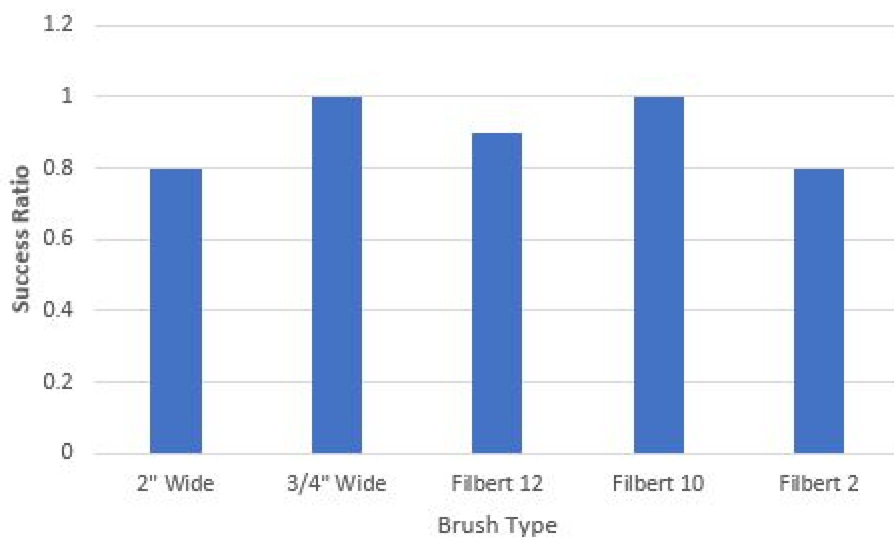

Figure 21: Success ratio with different brush types. 2” Wide and Filbert Size 2 brushes have 80% success rate. Analysis is independent of iteration number.

Testing Protocol for Adjustability

Purpose: The purpose of this protocol is to test the functionality and adjustability of the joystick mechanism used for adjusting the paintbrush position. This test was not adapted from any outside source.

Procedure: The procedure involves 10 test participants who will use the joystick mechanism to move the brush in specified directions. 5 participants will be of good health, without any known dexterity issues (control). 5 participants will be ATE patients, who regularly attend art therapy sessions and are part of the target population.

The participants will be asked to move the brush into specific positions using the joystick. The degree of accuracy each movement will be recorded. The positions are as follows:

1. 90° straight downward from starting position (centered in middle)
2. 90° to the left from the center
3. 90° to the right from center
4. 90° upward from the center
5. Return brush to starting position at center

Each movement will be repeated 3x for each participant, and the error will be measured using a protractor. These scores will be used to help evaluate the "Adjustability" constraint.

Results: The results of this test will be used to evaluate adjustability. The error (in degrees) of each position for each participant will be averaged. The average error for each group (control group, ATE patients) will also be calculated. We can use a t-test to compare the error for each group, as well as overall data. We expect the average error for each patient to be less than 5°, indicating the design is feasible and easily adjustable.

Testing Protocol for Low Cost of Production

Purpose: The purpose of this protocol is to determine whether the cost of production of this device is lower than the metric given in our metrics table of $50.

Procedure:

1. Obtain a list of materials needed to make the device.
2. Determine how much of each material is needed to make one device.
3. Determine the cost of each material for the amount needed to make one device.
4. Add the values found in Step 4 to get the total cost of production of one device.

Results: We performed this protocol when we completed our Anticipated Cost. **Table 6** gives the breakdown of the cost as well as the total cost of production of $43.10. This is below the $50 metric for low cost of production.

Testing Protocol for Measuring Weight

Purpose: The purpose of this test is to provide a method to test the weight of the entire device. This protocol was not adapted from any previous works.

Procedure:

1. Obtain a weighing scale large enough to fit the entire device. If possible, have the scale output the result in ounces for added accuracy.
2. Place the device on the scale and record the output.

Results: Given the lightweight nature of the PLA and ABS plastics, we estimate that the weight of the entire device will be under 8 ounces. Since we do not have a physical prototype, we are unable to test this metric, yet we can make an educated prediction based on material selection. The component of the design that would garner the most weight would be the circuitry due to its size and number of elements. Yet, in the final design, the circuit components are intended to be smaller and more compact, only further reducing the weight of the device.

Testing Protocol for Portability

Purpose: The purpose of this protocol is to determine whether the device is portable, specifically whether it measures less than 1 ft in length.

Protocol:

1. Acquire the device.
2. Measure the device in all directions.
3. The device passes if all dimensions measure less than 1 ft.

Results: Although we are unable to physically measure a prototype of the device, we do know the dimensions of the device shown in **Figure 5**. The maximum length of the Cross Hand Grip measures 6.5 in., while the height of the device (cross hand grip + ball-and-socket + brush holder) is 3 in. We can conclude that the device measures less than 1 ft. in every direction.

Testing Protocol for Compressive Strength

Purpose: The purpose of this test is to provide a method to test the durability of the device. This test is a variation of the slow-crack-growth test found in ASTM standard C1834 - 16.[48]

Protocol:

This test attempts to target compressive strength (see **Appendix A** - Justification for Durability)

1. Take a picture of the device prior to loading.
2. Load device onto Instron machine. (see **Figure 20**)
3. Set load to 322.5 N (see calculation below).
4. Repeat 52 times and then take a picture.
5. Compare the before and after picture and record observations. Pass/fail whether the device is still functioning following testing.

Figure 20: Testing orientation of device. This orientation is most likely to experience compression when used and when in storage. Since the push button lock is on the top of the device, it will also experience the load. This will not only test the durability of the device as a whole, but the durability of the button following extended use.

Results: Since we do not have a physical prototype, we are unable to test the device for this metric, yet we can predict the result as a pass. The stress load of 250 kPa equivocates to the stress that the device would undergo under weekly use and storage. Given that the load of 322.5 N is relatively lightweight, we shant worry about the device cracking under pressure. In fact, the ABS plastic is a rather durable plastic, with a compressive strength of 65 MPa.[22]

Calculation:

- Cross Sectional Area At Point of Contact = Base of Cylindrical Brush Holder = 2 in^2 = 12.9 cm^2
- 250 kPa = 250000 N/m^2 $\rightarrow$ 250000 N/m^2 * 0.00129 m^2 = 322.5 N

Testing Protocol for Replacement Parts

Purpose: The purpose of this protocol is to determine whether replacement parts for the device can be ordered on Amazon and easily implemented after purchase.

Procedure:

1. Acquire Anticipated Cost table.
2. Go through the items listed and determine which of them have Amazon listed as Vendor. Mark those items as "Pass."
3. Go through the remaining items and attempt to find them on Amazon. If found, mark the item as "Pass." If not found on Amazon, mark the item as "Fail."
4. If all items can be found, the device as a whole passes the metric, but if any one item cannot be found, the device as a whole fails to meet the Easily Found Replacement Parts metric.

Results: As shown in **Table 10**, each item received a passing mark. Although some items may require purchasing of a different brand when purchased from Amazon, they will functionally work as a replacement in the device. These items can also be purchased directly from the vendor provided if the user chooses to do so. Since each item can be found on Amazon, it is fair to conclude that replacement parts can easily be found for this device and the metric is met.

Table 10: List of items needed for device, with description, where the item may be purchased, and whether the item can be found on Amazon. If the item can be found on Amazon, "Pass" is denoted in the right hand column.

Vendor	Company	Reference	Description	Item Number /SKU/ASIN	Pass/Fail
Amazon	Overture	[27]	1.75 mm PLA 3D Filament (332 m spool)	B07PGY2JP1	Pass
Amazon	Jack Richeson	[28]	1/16 in. Armature Wire (2 32' spools)	B01B0Y06SA	Pass
Amazon	Goody Ouchless	[29]	4mm Elastic Band (27 count)	B00DFSHD5O	Pass
Mood Designer Fabrics	Mood Designer Fabrics	[30]	Black Stretch Polyester Mesh	306806	Pass (found on Amazon)
Amazon	Gorilla	[31]	Epoxy Adhesive (0.85 oz)	B001Z3C3AG	Pass

Banggood	Southco	[24]	Push-Button Switch Latch	1574777	Pass (found on Amazon)
Banggood	Geekcreit	[22]	Joystick Controller	76465	Pass (found on Amazon but currently unavailable)
Banggood	Geekcreit	[32]	Arduino Board	68537	Pass (found on Amazon without cable)
Banggood	Banggood	[33]	Circuit Breadboard	91872	Pass (found on Amazon, different brand)
Banggood	Banggood	[34]	Jumper Cable Wires (40pcs)	994061	Pass (found on Amazon, different brand)
Amazon	Deegoo	[23]	Servo Motors (4pcs)	B07MLR1498	Pass
Amazon	AmazonBasics	[35]	Battery (8pcs)	B00MH4QM1S	Pass
Amazon	Octave	[36]	ABS 3D Printer Filament*	B0083HSPH2	Pass

Testing Protocol for Ease of Use and Aesthetics

Purpose: The purpose of this test is to test the "easy to use" and "aesthetically and sensory pleasing" metrics found in **Table 2**. This has not been adapted from any outside source.

Procedure: A random group of ATE patients will be selected to test the device during one of their regular therapy sessions. After a demonstration on how to use the device, the artist will be free to use it while painting as they would normally. Following the session, they will be asked to complete the "Ease of Use Survey" and "Aesthetics Survey" found in **Appendix C**.

The ease of use survey gives a list of seven statements that individuals will give a score 1-5 based on how much they agree. The overall score for each individual will be calculated by finding the average score for the seven statements. This process will be repeated for the aesthetics survey, which gives the artist a list of five statements to score. Full surveys can be found in **Appendix C**.

Results: We will calculate the total score for each survey by averaging the overall scores given by each individual. Our device will pass each test if the total score is calculated to be greater than 4. Due to the online format of this course, we were unable to complete testing. However, hypothesized test results are summarized in **Table 11** below.

Table 11. Hypothesized results for the Ease of Use and Aesthetics surveys.

	Average Score	**Results**
Ease of Use	4.4 ± 0.5	Pass
Aesthetics	4.0 ± 0.3	Pass

Testing Protocol for Cleanability

Purpose: The purpose of this test is to test the "easy to clean" metric found in **Table 2**. The visibility scale used to determine cleanliness has been adapted from the ASTM standard D5913-96.

Procedure: A random group of ATE patients will be selected to test the device during one of their regular therapy sessions. After a demonstration on how to use the device, the artist will be free to use it while painting as they would normally. Following the session, brushes and the device will be cleaned according to regular ATE protocols. Paint visibility following cleaning will be judged by an objective third party, according to the visibility scale found in Appendix C. Each brush/device will be judged by three people, all ATE workers or patients.

Results: The average paint visibility score for each brush/device will be calculated, and those scores will be averaged for an overall score. The device passes the test if overall paint visibility after cleaning was less than two on the scale. We are not able to complete testing due to the online nature of this course. However, we hypothesize that our prototype will pass and have an overall score less than two. This is because the device is made mostly from plastics that paint can be easily removed from. Furthermore, the electronics portion of the device will be away from the user's dominant hand, and therefore will not be at risk of paint exposure.

Appendix J: Design Failure Modes and Effects Analysis

Table 12. Design Failure Modes and Effects Analysis

System/ Function	Potential Failure Mode	Potential Effects of Failure Mode	Severity	Potential Causes of Failure Mode	Current Design Controls	Occurrence	Current Detection Activities	Detection	RPN	Recommended Actions
Cross Hand Grip	Elastic band becomes worn out	Elastic band is too loose on user and doesn't provide security	4	Repeated stretching over a long period of time	Using a standard hair tie thickness which usually holds well over time	4	Fatigue Testing using Instron	1	16	- Use thicker band - Create advisory precaution to warn users not to excessively stretch band
	Elastic band snaps	Elastic band can't be used, doesn't provide security	5	Stretched too far	Using a standard hair tie size which is often easily placed around the wrist	3	Fatigue Testing using Instron	1	15	- Use thicker band - Create advisory precaution to warn users not to excessively stretch band
	Mesh becomes worn out	Material is loose on fingers and fingers are no longer supported	4	Repeated stretching over a long period of time	Using a compressive mesh	6	Fatigue Testing using Instron	1	24	- Use thicker mesh - Create advisory precaution to warn users not to excessively stretch band
	Mesh	Fingers	5	Epoxy fails to	Using a strong	2	Tensile	4	40	Investigate use of

	detaches from “X”	cannot go through the material and will not be supported		hold materials together	epoxy glue specific to holding two different materials together		Strength Testing using Instron			stronger epoxy glue, and then retest. This epoxy glue should have a stronger ultimate compressive and tensile strength than the previously used glue.
	Armature wire becomes worn out	Cross Hand Grip cannot be bent and hold its shape, user cannot wrap straps of “X” around hand, device is not secured on user’s hand	7	Bad material quality	Using high quality armature wire	1	Creep Test	2	14	Investigate use of stronger armature wire, and then retest. This new armature wire should be more ductile than the previously used armature wire
Ball-and-Socket	Electronics fail	Brush’s position cannot be controlled by the user using the joystick	8	1. Connections aren’t secure 2. Wire breaks 3. Breadboard breaks 4. Motors stop moving	Check all connections before using product, only buy high quality electronics	3	Use multimeter to detect the functionality of each electric component	2	48	- Use higher quality products that can carry current more efficiently than the others. -Wires should be more ductile and conductive

	Joystick breaks	Brush's position cannot be controlled by the user using the joystick	8	1. Joystick controller breaks 2. connection to circuit isn't secure,	Check user reviews before purchasing	2	Compressive Strength Testing using Instron	1	16	-Offer replacement joystick of higher quality -Use a stronger plastic coating other than ABS
	Cylinder/ ball attachment breaks	The joystick still controls movement, but the brush is no longer attached and	7	Epoxy glue isn't strong enough	Using a strong epoxy glue specific to holding two different materials together	2	Tensile Strength Testing using Instron	4	56	Investigate use of stronger epoxy glue, and then retest. This epoxy glue should have a stronger ultimate compressive and tensile strength than the previously used glue.
Cylindrical Brush Holder	Brush isn't secured	User cannot lock the brush and cannot paint	8	1. Button Jams 2. Brush is too big or too small in width	Test different brush sizes	5	Testing Protocol for Fitting Various Brush Sizes and Lock Security	1	40	Oil the lock with every 10 uses and retest the device