Development of a Modular Below-Elbow Prosthesis with Bidirectional Signaling for Children

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Abstract

Today, many prosthetic options are too expensive for most individuals to obtain, causing a lowered quality of life for millions of amputees around the world. For children with a limb difference, it is even harder to obtain functional prostheses. The child outgrows the limb too quickly and new prostheses are needed every 12-18 months. To combat the price barrier surrounding advanced prostheses, a modular myoelectric prosthesis model was created. The movement control of the myoelectric was implemented through an Arduino-microcontroller powered by servo motors and photoelectric sensors by way of electrical signals emitted from muscles. The modular prototypes were developed with many different 3D-printed materials, infill levels, Arduino code, and movement mechanic designs, then tested on five specific criteria: functionality, modularity, durability, comfort, and cost-effectiveness. Due to its modularity, the prosthesis will be more accessible to children who cannot afford to buy new ones as the older models are outgrown. For this project, bidirectional signaling between the prosthesis and the user was a major focus of this project so that the user would be able to feel simple sensations with the prosthesis. A cheaper, 3D-printed, and modular below-elbow myoelectric prosthesis will allow children to grow up with and utilize prostheses to a greater extent. The best prototype, according to the criteria, was selected via an engineering design matrix. Testing showed that the prototype performed at 42% the functionality of a human arm. Future work will be geared toward implementing permanent electrode sensors and continuing to improve upon the criteria.

Keywords: sensory feedback, 3D printed, durability, comfort, cost-effective, myoelectric

Graphical Abstract

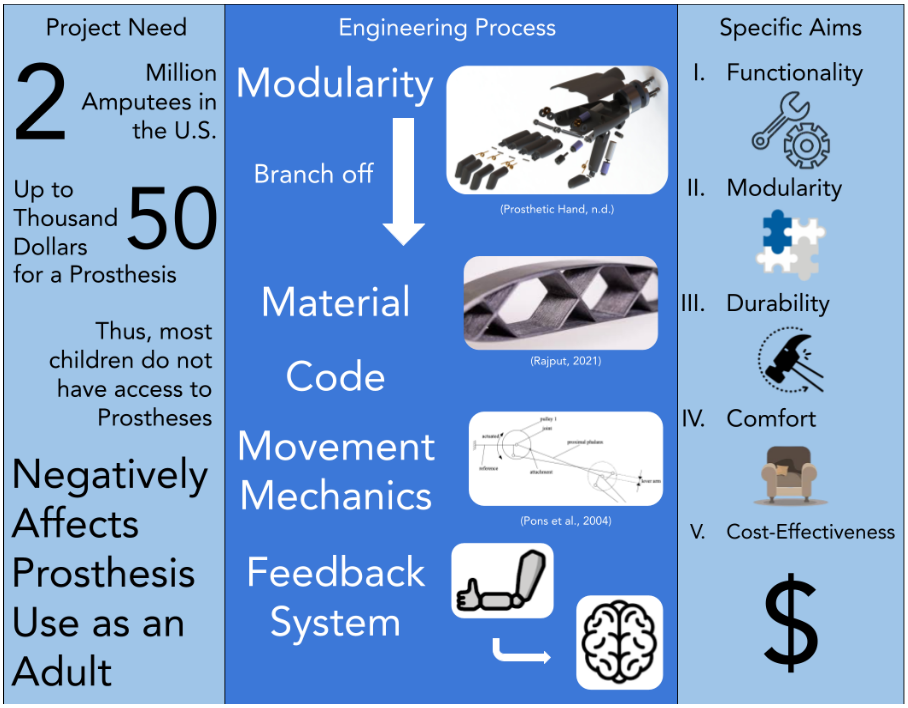

Figure 1: Graphical Abstract (Made by T. Tran in Google Drawings, 2022).

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I would like to give a special thanks to Dr. Kevin Crowthers, Ph.D. and Mr. Pavel Loven for their advice, time, and support throughout the journey of this research project. Without their help, none of this would have been possible.

Development of a Modular Below-Elbow Prosthesis with Bidirectional Signaling for Children

There are over two million amputees in the United States, and many cannot afford prostheses (Appendix A), especially children who grow out of them quickly (Zhu et al., 2022). The price of body-powered prostheses ranges from $4,000 to $50,000, while the price of an externally-powered prostheses costs from $25,000 to $50,000 (Cabibihan et al., 2018). Modern prostheses are expensive because each one of them must be personalized. Each situation is different, so there is no way to generalize the traditional silicone casting process, which is time consuming and labor intensive. Most child amputees do not grow up using a prosthesis because of costs and sizing, decreasing the likelihood of prosthesis use as an adult (Huizing et al., 2010). The absence of prosthetic use during childhood can cause detrimental effects to the user's use later in life as it depends on the age the prosthesis is fitted (Huizing et al., 2010). The children are not used to operating daily life activities with a prosthesis. The older the children get, the harder it will become for them to adapt to using a prosthesis.

Background

To combat this price barrier surrounding advanced prostheses, a modular prosthetic design can be developed to grow with the user. The unique aspect of modularity has not been found predominantly in the field yet and is the main innovation being targeted. No other prosthesis accommodates growing children in this way. With 3D printing, a shape-changing prosthesis was created to address personalization and cost. Modular parts of the prosthesis will be added on by a prosthetist (a healthcare professional who fits prostheses) without needing to change the design. A dynamically changing prosthesis made utilizing pressure sensors, an airbag, and a pump, similar to a shape-changing cast, was also considered as an option (Shoshan & Shamaev, 2015). As an arm grows, it will create more pressure against the prosthesis. The pump will then change the size of the airbag (underneath the prosthesis) size to accommodate for the increase in pressure. This airbag concept has been prototyped. However, it only expands and contracts for extra support when the prosthesis is in use (Sang et al., 2014). This novel socket design utilizes four spring-air pump systems located around the socket to change its size (Sang et al., 2014). This design will be expanded to create a shape-changing prosthesis for growing children as its primary objective. Using a modular design for childhood prostheses can increase overall comfort and acclimate children to use prostheses for the rest of

Figure 2: Novel socket design. Airbag and pump powered shape-changing prosthetic socket (Sang et al., 2014).

Figure 3: Prosthetic Fin Attachment. Designed to attach to prosthesis for swimming (Freestyle Swimming Device, n.d.).

their lives. The closest conceptual design resembling the modularity is hand attachments for prostheses and modularly designed prostheses software (Johannes, 2011). For example, consider a fin attachment for a prosthesis so that the user can swim better (Johannes, 2011). Or, consider an algorithm on a microprocessor that can be used for a multitude of prostheses (Johannes, 2011). Therefore, there is essentially nothing in the field which can be compared to the modular design pursued in this project.

Another important aspect of prostheses to consider when designing them is the type of prosthesis. There are currently many different types of prostheses in the field, all utilizing different technologies, mechanics, and targeting different patient groups. The most prevalent prosthesis types are passive, body-powered, myoelectric, and hybrid (Smail et al., 2021). Passive prostheses are simply for aesthetics, have no functional ability, and are made of mostly silicone, plastic, and paint. Passive prostheses are also the cheapest type of prosthesis (Smail et al., 2021). Next, body-powered prostheses have functional use, but have no electrical parts to them. Usually fitted with a shoulder harness and hook, body-powered prostheses are the simplest and cheapest functional prostheses (Smail et al., 2021). Myoelectric prostheses are more advanced than the body-powered prostheses and require an external power source, usually a rechargeable battery. Myoelectrics take input and move the prosthetic limb with motors by utilizing electrodes connected to the muscles on the residual limb. Myoelectric prostheses are on the pricier side because of the batteries, electrodes, and motors (Smail et al., 2021). Lastly, hybrid prostheses are a combination of both myoelectric and body-powered prostheses. Hybrid prostheses have the harness of a body-powered prosthesis with the electric motors and electrodes of a myoelectric. Because of this, a hybrid prosthesis's price might range from a little more than a body-powered prosthesis to more expensive than a myoelectric (Smail et al., 2021). Bidirectional signaling is also starting to be incorporated into myoelectrics. Sensors can be implemented into a myoelectric so the user can receive some type of sensation when the prosthesis touches something. The myoelectric discussed in this paper will incorporate this functionality as well. This process is currently being improved by machine learning and artificial intelligence algorithms to predict the movements the user desires.

There are three main ways to map out the mechanical control of a myoelectric prosthesis: sequential control (SeqCon), direct control (DirCon), and mapped control (MapCon) (Zhu et al., 2022). SeqCon utilizes "modes" within the prosthesis. When the user contracts a certain muscle, the prosthesis will move. When the user contracts a different muscle, the microprocessor on the myoelectric will switch modes on the prosthesis. Now, the original muscle contracted will control a different operation on the prosthesis. DirCon maps out certain prosthesis movements to specific muscle contractions (via the microprocessor code) (Zhu et al., 2022). Contraction of muscle x will control movement x, and contraction of muscle y will control movement y. MapCon is similar to DirCon, but instead, the mappings are inverted. Contraction of muscle x will control movement y, and contraction of muscle y will control movement x. The most common movements which myoelectrics mimic are open-close (Opn-Cls), pronation-supination (Pro-Sup), extend-flex (Ext-Flx), and radial-ulnar (Rad-Uln) movements (Zhu et al., 2022). SeqCon, compared to both DirCon and MapCon, is inferior because it is not as effective in multiple degree of function (DoF) situations (Zhu et al., 2022). The lack of effectiveness is why the project will focus on only DirCon and MapCon myoelectric control.

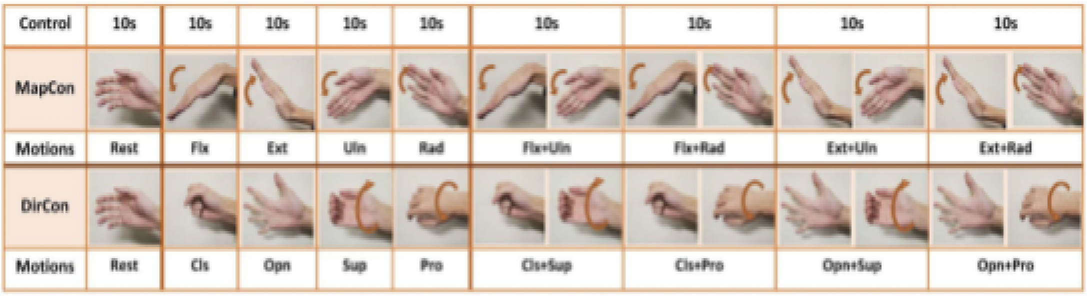

Figure 4: MapCon and DirCon. Common myoelectric movements with MapCon and DirCon control (Zhu et al., 2022).

A critical part in the creation of prosthesis is the material of the prosthesis. The main materials used to create prostheses are silicone, carbon fiber, polymers, aluminum, and titanium (Mota, 2017). Silicone is mostly used for the liner of the prosthesis, separating the skin of the residual limb from the prosthesis, like how a sock separates a foot from a shoe. Carbon fiber can be used for almost all parts of the prosthesis. Carbon fiber can be used to create the fingers/hand as well as the socket for the residual limb. Its main advantages are that it is light and durable. However, carbon fiber is expensive and hard to 3D print. Polymers are used in the same fashion as carbon fiber as a cheaper alternative. Polymers are weaker and less durable compared to carbon fiber and can also be heavier. Aluminum and titanium, two similar metals, are used in creating some of the joints in a prosthesis. A high stress part, joints have to be made of strong materials. Aluminum and titanium are used more in body-powered prostheses because they are supported by shoulder harnesses and can handle the added weight. Hooks are usually made from those metals as well (Mota, 2017).

Currently, a high percentage of amputees who receive prostheses abandon them and never use them again (Smail et al., 2021). The abandonment wastes the user's money and lowers their quality of living. The leading cause of prosthesis abandonment is comfort. Additionally, the main issues users find with their prostheses are that they are heavy, hot after an extended period of use, rigid, and bulky (Smail et al., 2021). In addition, users abandoned prostheses without sensory feedback, listing the lack of sensation as the cause of abandonment (Smail et al., 2021). Users who abandon their prostheses feel like it is not a part of them and they could function better without it. This project will focus on improving these comfort-related prosthetic issues.

To help implement the prosthesis design, Backyard Brains's "The Claw" was utilized as a proof of concept and guide. Backyard Brains is a company that creates neuroscience tools that utilize the human nervous system to control computers and robots. One of their products, "The Claw," will be used as the subject model in experimentation. The product comes with electrodes, an Arduino (microcontroller computer), and a plastic claw that can be controlled by the user (The Claw, n.d.). When the electrodes sense a muscle contract, an EMG signal (electromyography signals, or electrical signals which the brain sends to muscles to control them) is relayed to the Arduino. The Arduino, coded in C++, then takes that signal to control a servo motor which rotates to move the plastic claw.

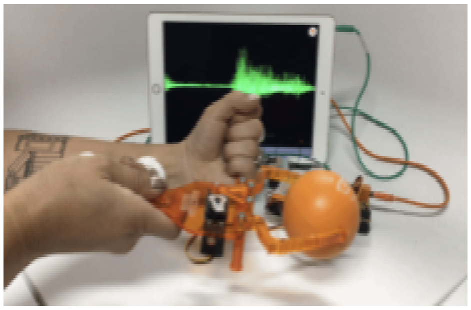

Figure 5: The Claw from Backyard Brains. Arduino also connected to tablet to visualize the strength of the EMG signals (The Claw, n.d.).

Graphical Background

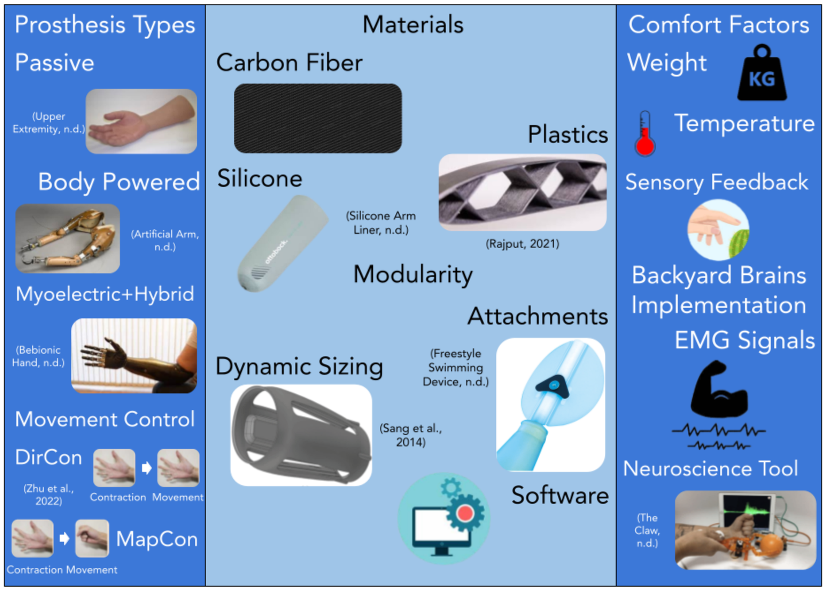

Figure 6: Graphical Background (Made by T. Tran in Google Drawings, 2022).

Objectives

Along with the main goal of creating a modular 3D-printed prosthesis prototype, bidirectional functionality, durability, comfort, and cost-effectiveness will be specific focus points. Modularity, in conjunction with the bidirectional functionality of the prosthesis, allows children to grow up with prostheses at a cheaper cost with the functionality of a myoelectric.

The first and most important specific aim for this project is functionality. A prosthesis lacking functionality has no use. There will be three main trials to test the functionality of the prosthesis. The three main trials are stacking wooden blocks, hanging clothespins, and twisting a round doorknob with the prosthesis prototype.

The second aim for this project is modularity. Modularity is what will allow the prosthesis to adapt along with change in child size. As the residual limb of the child grows, so will the prosthesis. Modularity can be achieved in many different ways: modular plastic 3D-printed pieces that attach to each other, airbags and an air pump that will adjust the size of the prosthesis, or a combination of the two.

The third specific aim for this project is durability. If the prosthesis is not durable, the user has to adjust their life to the prosthesis when it should be the other way around. A lack of durability could ultimately lead to prosthesis abandonment, lowering the user’s quality of life. The user must be able to trust the prosthesis, and for that to happen, it must be durable and sturdy. Many different types of 3D-printing filaments at different infill levels will be tested in the creation of this prosthesis.

Comfort is the fourth specific aim for this project. One of the leading reasons for prosthetic abandonment is comfort. The prosthesis cannot be too heavy, rigid, hot, or bulky. The material used and the overall mechanical design for the prosthesis will determine these factors. Again, many different types of 3D-printing filaments at different infill levels will be tested in the creation of this prosthesis.

The last specific aim for this project is cost-effectiveness. Emphasized throughout this project, cost is one of the main hindrances of prostheses being widely available for both adults and children. Although the budget for this project is 2000 USD, the majority of that is not anticipated to be used. In addition, 2000 USD is only a fraction of the cost of current prostheses.

Process of Product Design

The project focuses on the five specific aims including, safety, control, and sensory feedback. During the design process, a 3D printer will be utilized to print most of the parts of the prosthetic prototypes. For the Arduino system, there will be two systems of input and output running through the same Arduino. The first system is composed of input from the EMG electrodes (adhered to the user's skin inside of the prosthesis socket) to the servo motors that control the movement of the prosthetic arm. The second system is composed of photoelectric sensors (which detect change in light intensity) on the tips of the prosthetic fingers which trigger vibration motors on the inside of the prosthetic socket. In this way, the user will receive sensory input. Note, along with the photoelectric sensors, infrared sensors will also be tested as well. The functionality testing will be similar to Zhu et al. (2022) where the Arduino/Backyard Brain apparatus will be used to test each prosthetic prototype. For the prototype, different materials, movement mechanics, and modular approaches will be tested. The prototype will then be compared to the baseline performances of "The Claw" and of a normal human arm. Future work will be geared toward implementing permanent electrode sensors and continuing to improve upon the criteria via new designs and materials.

Section II: Methodology

Role of Student vs. Mentor

The work done by myself was all of the research, prototyping, testing, analysis, and scientific writing needed for the completion of this project. The work I had assistance with was the 3D printing of the parts of the prostheses and the assembly of some of the parts of the prostheses (assisted by Dr. Kevin Crowthers, Ph.D., and Mr. Pavel Loven). This project was completed over a six-month period.

Equipment and Materials

The materials list is as follows. Backyard Brain's The Claw Kit (software C++ in the Arduino IDE), Arduino kit (with various sensors, motors, and cables), Arduino power shield, Solidworks CAD modeling software, able-bodied human subject, clothespins, a door with round doorknob, wooden blocks (the size of a Jenga piece), a 3D printer (software Solidworks) with filament (different polymer types and carbon fiber), silicone liners,

Figure 7: Equipment and materials for the methodology (Taken by T. Tran, 2023).

aluminum/titanium/copper wire, resistors, 9V batteries, photoelectric sensors, EMG sensors, vibration motors, servo motors, and transistors.

General Testing Strategy

Prototypes of the prosthesis will be attached to “The Claw”. The Arduino code was modified to control the prosthetic prototype. The testing will be similar to the testing in “Myoelectric Control Performance of Two Degree of Freedom Hand-Wrist Prosthesis by Able-Bodied and Limb-Absent Subjects” (Zhu et al., 2022). The three main trails of the article will be followed: block stacking, hanging clothespins, and opening and closing a doorknob. The Arduino/Backyard Brain apparatus will test each prosthetic prototype. For the prototype, different materials, movement mechanics, and modular approaches were tested. The prototype will then be compared to the baseline performances of “The Claw” and a normal human arm. Each of the five specific aims will be tested for.

Technique 1 - Functionality Methodology

Test one will be a timed block stacking trial. The independent variable will be one of the following: material, Arduino code, movement mechanics, or modularity design. The dependent variable is the time it takes to stack the blocks. The controls will be each of the possible independent variables which were not selected for the specific trial. There will be three iterations of each prototype.

The second trial will be putting clothespins on a pole, and measuring the numbers placed within a 2-minute period. The number of clothespins placed will be measured. The independent variable will be one of the following: material, Arduino code, movement mechanics, or modularity design. The dependent variable is the number of clothespins hung. The controls will be each of the possible independent variables which were not selected for the specific trial. There will be three iterations of each prototype.

The third trial will be opening and closing a door with a circular doorknob. This trial will test the DoF (degrees of freedom) functionality of the prosthesis because it takes multiple muscle groups to twist the knob. There will be a two minute timer, and the number of times the door is opened and closed will be measured. The independent variable will be one of the following: material, Arduino code, movement mechanics, or modularity design. The dependent variable is the number of times the door was opened and closed. The controls will be each of the possible independent variables which were not selected for the specific trial. There will be three iterations of each prototype.

Justification and Feasibility

The three trials to test for functionality are relevant because they all test different types of motor skills that a human arm would have. As mentioned before, these three trials have been inspired by Zhu et al. (2022).

Technique 2 - Modularity Methodology

To test and determine the quality of modularity in a prosthesis prototype, the model will need to be able to grow to various sizes while keeping its functionality. To test this, the functionality trials should be run again at different sizes

Justification and Feasibility

Testing the prosthetic modularity is relevant because it is quite straightforward to test it and because it shows whether or not the prosthesis prototype can work for the child at each different size/age which the child needs the prosthesis for.

Technique 3 - Durability Methodology

Two different material tests must be conducted to test the prosthetic durability. More specifically, a stress analysis on the software SolidWorks and an everyday degradation test. Various 3D printing materials will go through this testing; different polymers, materials, and infill (hollowness) levels will be tested.

Justification and Feasibility

The stress and degradation tests are relevant because those two forces are the most likely to be put upon the prosthesis during use. If those two tests are satisfied by a prosthesis model, then that model will be durable when it is put through the usual forces of everyday use (15MPa).

Technique 4 - Comfort Methodology

To determine the levels of comfort for each prosthesis prototype, two tests will be conducted: rigidity and weight. Rigidity and weight are two of the leading contributors to prosthesis abandonment, and if they are reduced, the prosthesis will become more comfortable for the user to wear. Each prototype will be weighed upon completion, and the number of rigid points and edges will be counted on the CAD model.

Justification and Feasibility

Weighing the prosthesis is the only way to get a quantifiable value for how heavy the prosthesis will be when worn by the user and is therefore justifiable. Because rigidity is not necessarily a quantifiable value, the number of points and edges is one of the best ways to portray this feature as a number.

Technique 5 - Cost-effectiveness Methodology

To determine the cost-effectiveness of each prosthesis prototype, the cost of all of the parts of the prototype will be aggregated.

Justification and Feasibility

Quantifying the cost of each prototype is justifiable because lowering the cost of the final prototype would allow more children to access this product. The hardest part of this section would be to calculate the cost of the filament used to 3D print the prototype.

Statistical Tests

To test for statistical significance, a standard t-test was used to compare two individual prototypes to each other or the baseline/human arm. A standard t-test was used because it is a statistical test used to compare the means of exactly two groups. In addition, a one-way ANOVA (analysis of variance) test and post hoc test were used to compare all prototypes to each other simultaneously (including the baseline and the normal human arm). If an ANOVA produces a p-value less than the significance level, a post hoc test can be used to find out which groups differ from one another.

Procedure

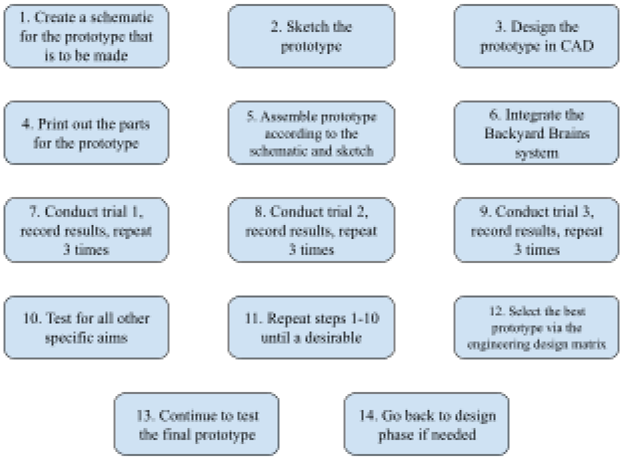

Figure 8: Procedure infographic for prosthesis prototyping and testing (Made by T. Tran in Google Drawings, 2022).

Ethics

There is little to no risk of harm when using The Claw from Backyard Brains in testing. There is not enough voltage to harm the human testing the prosthesis. Some precautionary practices are to clean the area where the electrode will be placed on the skin and ensure that the area is dry. It should be made sure that there is smooth contact between the electrode and the skin of the user.

Section III: Results

Backyard Brains Baseline

The baseline for this project, as described before, is Backyard Brains' "The Claw." All prototypes were compared against it to determine performance. This apparatus consists of electrodes, an Arduino (microcontroller computer), and a plastic claw which can be controlled by the user (The Claw, n.d.). When the electrodes sense a muscle contract, an EMG signal is relayed to the Arduino. The Arduino was pre-coded in C++, and no additions were made to the original code for this baseline. "The Claw" also has the ability to switch between DirCon and MapCon with a button on the physical Arduino.

Figure 9: Backyard Brains' "The Claw" (Photo taken by T. Tran, 2022).

Functionality Test

The results of the three functionality trials for the Backyard Brains baseline are shown in the graphs below. As the trials went on, the use of the prosthesis improved over time and showed great promise for a baseline. The N number in this case was 3.

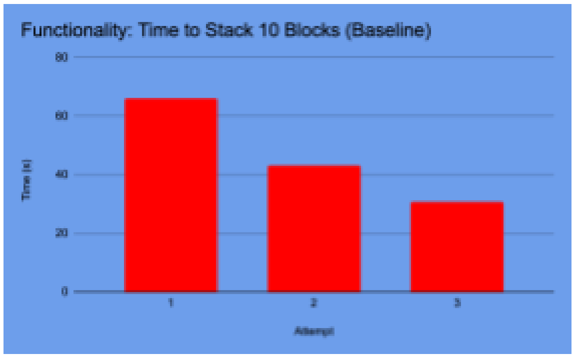

Figure 10: Graph of the Backyard Brains functionality trial 1 (Made by T. Tran in Google Sheets, 2023).

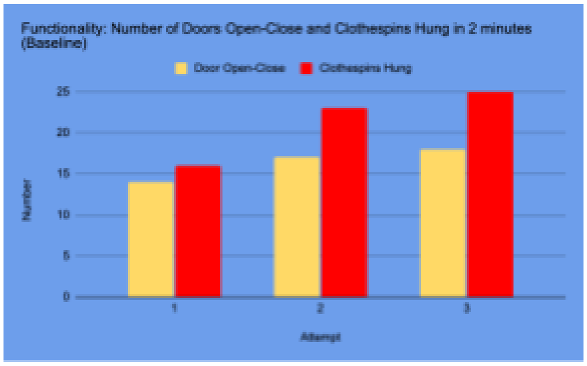

Figure 11: Graph of the Backyard Brains functionality trials 2 and 3 (Made by T. Tran in Google Sheets, 2023).

Durability Test

The plastic was quite strong with wear and tear; however, Backyard Brains did not provide the specific plastic material, so a stress analysis could not be done on Solidworks. There was around a 500g load on the Backyard Brains' "The Claw."

Comfort Test

The Backyard Brains baseline did not have any wearable aspect to the design, so the edges cannot be counted for this test. The whole apparatus weighs 93g.

Cost-effectiveness Test

The cost of "The Claw" was around 200 USD.

Criteria (Rank)	Backyard Brains "The Claw"	Reasoning
Safety - how safe the user feels when using the prosthesis; how well the user trusts the prosthesis (10)	9	Very safe, almost no potential sources of harm

Functionality - determined from functionality methodology (9)	5	Not as functional as it needs to be, but can still do some trials well
Modularity - determined from modularity methodology (9)	0	Not modular
Comfort - determined from comfort methodology (7)	1	Had to be held in the other hand, not comfortable
Durability - determined from durability methodology (7)	6**	The plastic was quite strong**material unknown, 500g load
Cost-effectiveness - determined from cost-effectiveness methodology (6)	7	Not extremely pricey ($200)
Control - how well the user can manipulate the prosthesis to do desired actions (8)	5	Not great control but some control
Sensory Feedback - how well the prosthesis conveys the sense of touch to the user (8)	0	No sensory feedback
Total (Max 640)	266	

Figure 12: Engineering Design Matrix for the Backyard Brains baseline (Made by T. Tran in Google Sheets, 2023).

Human Arm

The performance of a human arm was also tested in this project to see how the prototypes and baseline would fair. The goal of any prosthesis is to get to 100% of the performance of a human arm.

Functionality Test

The results of the three functionality trials for the human arm are shown in the graphs below. Results were expected to be this great compared to the prostheses because it is a human arm. The ultimate goal for a prosthesis is to get to this level of human arm performance.

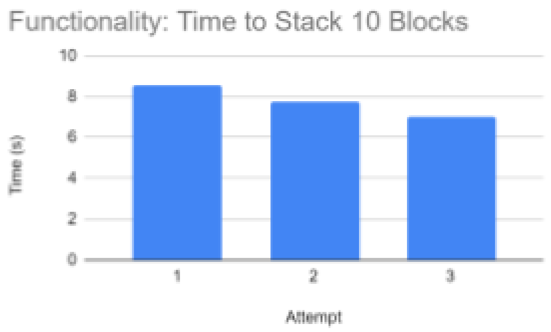

Figure 13: Graph of the human arm functionality trial 1 (Made by T. Tran in Google Sheets, 2023).

Figure 14: Graph of the human arm functionality trials 2 and 3 (Made by T. Tran in Google Sheets, 2023).

Criteria (Rank)	Human Arm	Reasoning
Safety - how safe the user feels when using the prosthesis; how well the user trusts the prosthesis (10)	10	No danger at all
Functionality - determined from functionality methodology (9)	10	Completely functional
Modularity - determined from modularity methodology (9)	0	Not modular
Comfort - determined from comfort methodology (7)	10	N/A
Durability - determined from durability methodology (7)	10	Human arm is very durable
Cost-effectiveness - determined from cost-effectiveness methodology (6)	10	No cost
Control - how well the user can manipulate the prosthesis to do desired actions (8)	10	Total control
Sensory Feedback - how well the prosthesis conveys the sense of touch to the user (8)	10	Total sensory feedback
Total (Max 640)	550	

Figure 15: Engineering Design Matrix for the human arm (Made by T. Tran in Google Sheets, 2023).

Prototype 1

Prototype one was created focusing on the functionality specific aim of the project and trying to improve on the baseline. Parts were modeled using computer-aided design (CAD) via the software Solidworks. A model from Maurya (2020) and an Ardunio housing design from Antoine (2022) were modified to accommodate modularity and comfort. A base part of the Arduino housing was melded to a 1/2 piece socket of the prosthesis design. The design was then 3D printed with a 35% infill level using PETG filament, as it was the only filament available. A 35% infill level was used because it strikes the perfect balance between weight and strength. As the infill level increases past 50%, returns become diminishing on strength. The prototype

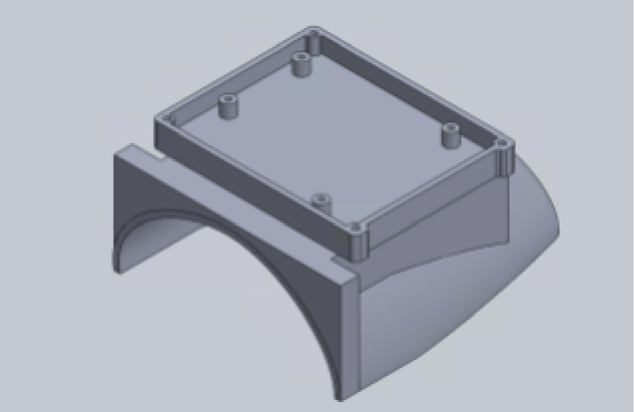

Figure 16: The Arduino-socket piece to the prosthesis (Made by T. Tran in Solidworks, 2023).

was then assembled after parts were sanded. To implement the software, some code was edited in the Arduino IDE (C++) and downloaded onto the Arduino Uno. A part of this implementation was both DirCon and MapCon, adapted from Backyard Brains (implemented in the baseline "The Claw"). An infrared sensor was implemented to sense touch by the user. In addition, the vibration motors purchased for the purpose of sensory feedback had to be soldered in-parallel with a 1000 ohm transistor to prevent overheating.

Figure 17: 3D printed prototype 1 (Made by T. Tran in Solidworks, 2023).

Functionality Test

The results of the three functionality trials for prototype 1 are shown in the graphs below. As the trials went on, the use of the prosthesis improved over time and showed gradual improvements. The N number in this trial testing was 3.

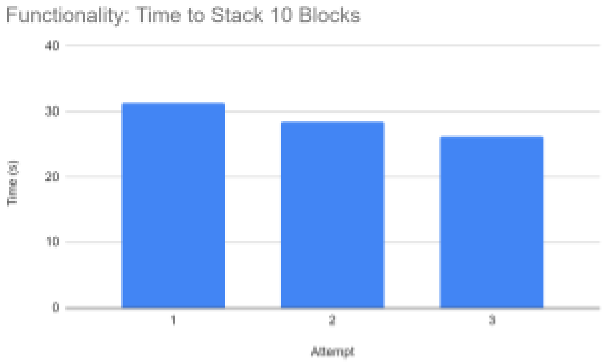

Figure 18: Graph of prototype 1 functionality trial 1 (Made by T. Tran in Google Sheets, 2023).

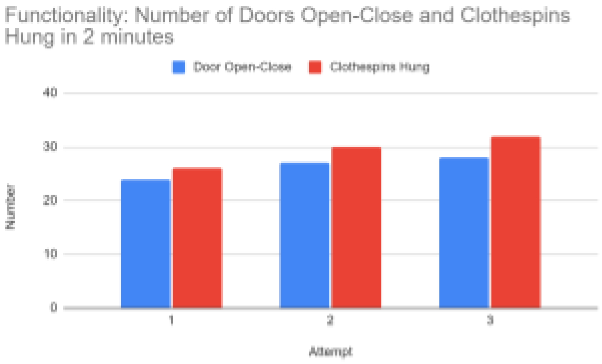

Figure 19: Graph of prototype 1 functionality trials 2 and 3 (Made by T. Tran in Google Sheets, 2023).

Modularity Test

Prototype 1 performed similarly to its original size when finger lengths were shortened.

Durability Test

Wear and tear for normal daily use is good. Stress test in Solidworks showed a value of 20MPa for PETG filament at a 35% infill level.

Comfort Test

Weight of 233g and a number of 4 rigid points on the outside of the socket that would be exposed to skin for the user.

Cost-effectiveness Test

The cost of printing prototype 1 was covered by the resources provided by Dr. Crowthers, but is substantially cheaper than the baseline price of 200 USD.

Criteria (Rank)	Prototype 1	Reasoning
Safety - how safe the user feels when using the prosthesis; how well the user trusts the prosthesis (10)	9	Very safe, almost no potential sources of harm
Functionality - determined from functionality methodology (9)	7	Performed in the trials fairly well
Modularity - determined from modularity methodology (9)	5	Fingers are modular, but the socket is not, performed similarly when fingers shortened
Comfort - determined from comfort methodology (7)	6	Decent, but the design is a little bulky
Durability - determined from durability methodology (7)	8	20MPa is fairly durable compared to the baseline
Cost-effectiveness - determined from cost-effectiveness methodology (6)	9	3D printing out of plastic is much cheaper than buying a whole prosthesis system

Control - how well the user can manipulate the prosthesis to do desired actions (8)	6	Controlling the prosthesis had a learning curve and was hard to control at times, especially for fine motor movements
Sensory Feedback - how well the prosthesis conveys the sense of touch to the user (8)	6	Vibration from motor was the only sensory feedback
Total (Max 640)	446	

Figure 20: Engineering Design Matrix for prototype 1 (Made by T. Tran in Google Sheets, 2023).

Prototype 2

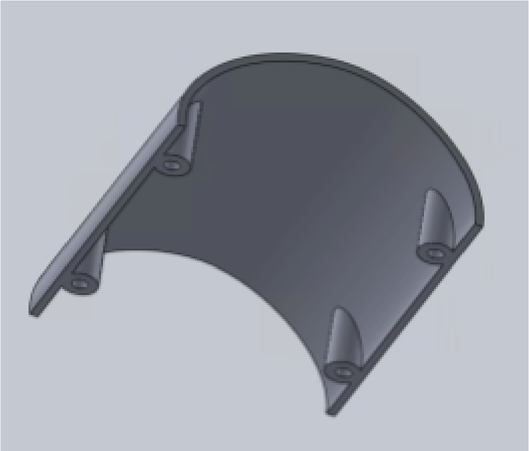

Figure 21: Part of the extra socket piece to the prosthesis (Made by T. Tran in Solidworks, 2023).

Prototype two was created focusing on the modularity specific aim of the project and trying to improve on the functionality of prototype 1. Parts were modeled using computer-aided design (CAD) via the software Solidworks. An additional modular part of the socket was added to the current socket, doubling its length and allowing the prosthesis to adjust for older and larger children. The design was then 3D printed with a 35% infill level using PETG filament, as it was the only filament available. The prototype was then assembled after its parts were sanded. The code was edited in the Arduino IDE (C++) and then downloaded onto the Arduino. A part of this implementation was both DirCon and MapCon, adapted from Backyard Brains (implemented in the baseline “The Claw”). An infrared sensor was implemented to sense touch by the user. In addition, the vibration motors purchased for sensory feedback and had to be soldered in-parallel with a 1000 ohm transistor to prevent overheating.

Figure 22: 3D printed prototype 2 (Made by T. Tran in Solidworks, 2023).

Functionality Test

The results of the three functionality trials for prototype 2 are shown in the graphs below. As the trials went on, the use of the prosthesis improved over time and showed greater improvements compared to prototype 1. The N number in this case was 3.

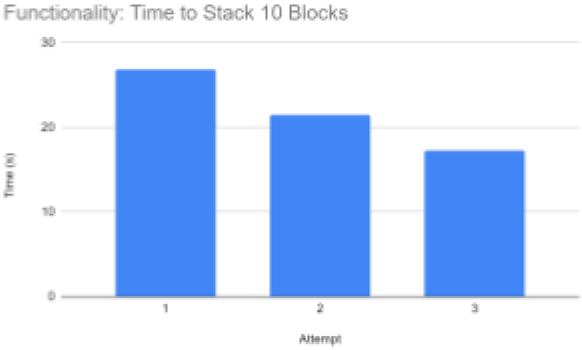

Figure 23: Graph of prototype 2 functionality trial 1 (Made by T. Tran in Google Sheets, 2023).

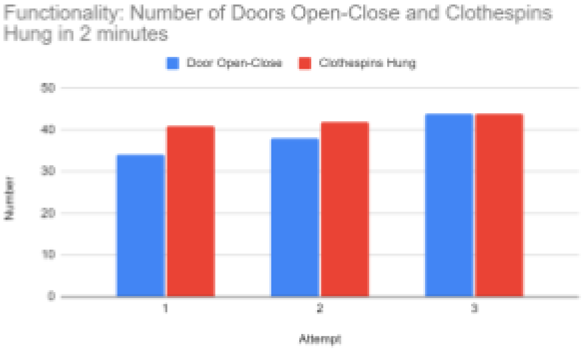

Figure 24: Graph of prototype 2 functionality trials 2 and 3 (Made by T. Tran in Google Sheets, 2023).

Modularity Test

Prototype 2 performed very similarly to its original size when finger lengths and socket lengths were shortened.

Durability Test

Daily degradation showed no damage for daily use. Stress test in Solidworks showed a value of 20MPa for PETG filament at a 35% infill level.

Comfort Test

Weight of 303g and a number of 1 rigid point on the outside of the socket that would be exposed to skin for the user.

Cost-effectiveness Test

The cost of printing prototype 2 was covered by the resources provided by Dr. Crowthers, but is substantially cheaper than the baseline price of 200 USD.

Criteria (Rank)	Prototype 2	Reasoning
Safety - how safe the user feels when using the prosthesis; how well the user trusts the prosthesis (10)	9	Very safe, almost no potential sources of harm
Functionality - determined from functionality methodology (9)	7	Performed in the trials fairly well
Modularity - determined from modularity methodology (9)	7	Fingers are modular, but the socket is not, performed similarly when fingers/socket shortened
Comfort - determined from comfort methodology (7)	6	Decent, but the design is a little bulky
Durability - determined from durability methodology (7)	8	20MPa is fairly durable compared to the baseline
Cost-effectiveness - determined from cost-effectiveness methodology (6)	9	3D printing out of plastic is much cheaper than buying a whole prosthesis system
Control - how well the user can manipulate the prosthesis to do desired actions (8)	6	Controlling the prosthesis had a learning curve and was hard to control at times, especially for fine motor movements

Sensory Feedback - how well the prosthesis conveys the sense of touch to the user (8)	6	Vibration from motor was the only sensory feedback
Total (Max 640)	464	

Figure 25: Engineering Design Matrix for prototype 2 (Made by T. Tran in Google Sheets, 2023).

Standard t-test

A standard t-test was performed comparing the means for the three functionality trials between prototypes one and two. All three resulted in p-values less than 0.05. Trial 1 (blocks) had a p-value of 0.02845, trial 2 (doors) had a p-value of 0.01621, and trial 3 (clothespins) had a p-value of 0.00431.

One-way ANOVA Test

A one-way ANOVA test was performed comparing the means for the three functionality trials between all prototypes, baselines, and the human arm. All three resulted in p-values less than 0.05. Trial 1 (blocks) had a p-value of 0.00599, trial 2 (doors) had a p-value of 0.0000000265, and trial 3 (clothespins) had a p-value of 0.000000017. The low p-value means that all three trials are eligible for the post hoc test to determine which groups are different.

Post Hoc Test

A post hoc test was performed comparing the variance for the three functionality trials between all prototypes, baselines, and the human arm. Trial 1 (blocks) had one p-value under 0.05: the baseline vs. prototype 2 with a p-value of 0.046. Trial 2 (doors) had all p-values under 0.05. Trial 3 (clothespins) had four p-values under 0.05: the baseline vs. a human arm (0.001), the baseline vs. prototype 1 (0.008), a human arm vs. prototype 1 (0.001), and a human arm vs. prototype 2 (0.001).

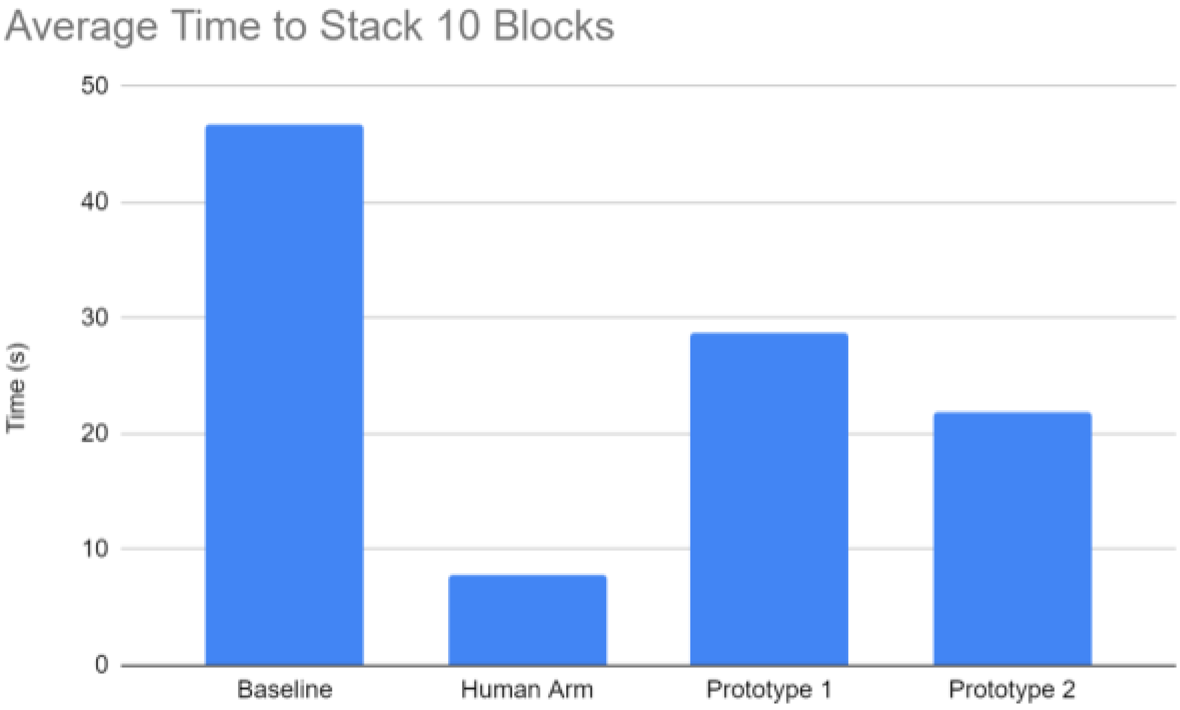

Figure 26: Graph of all prototypes functionality trial 1 (Made by T. Tran in Google Sheets, 2023).

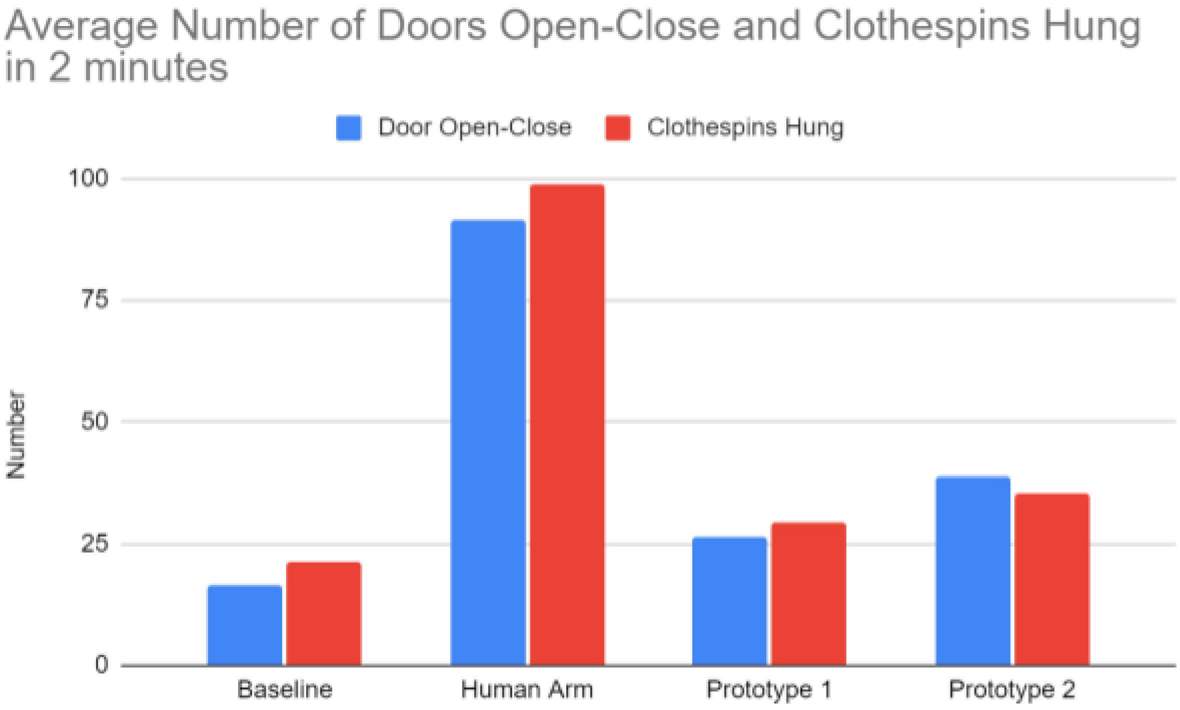

Figure 27: Graph of all prototypes functionality trials 2 and 3 (Made by T. Tran in Google Sheets, 2023).

Section IV: Discussion

Interpretation

Through the testing for the 5 specific aims, and analysis of the data, it can be confidently stated that the objectives for this project were achieved. A functional, modular, durable, comfortable, and cost-effective prosthesis with the target use for children was prototyped. There was statistical significance between the first and second prototypes as well as between the baseline and both prototypes ($p<0.05$ for all cases). More specifically, the price threshold of 200 USD and the stress value of 15MPa come to mind in addition to the rest of the data shown in the results section. Through the design matrices, it can also be seen that the second prototype is the better of the two prototypes developed. Looking at the data more closely, it can be seen that the second prototype performs at 42% of the rate a normal human arm would (functionality-wise). The statistical tests also point to this conclusion.

In the scope of the field of prostheses, this project introduces a new, modular type of myoelectric prosthesis with bidirectional signaling that has gone through preliminary testing. It contains many parts of previous work in the field, like taking inspiration from the experiments by Zhu et al. in 2022. This research might influence more prostheses to become modular and thus appeal to children in need by reducing the cost of total prostheses growing up.

Limitations

Some limitations in this project were the quality of the 3D printing and quality of the Arduino parts. Only one type of filament for 3D printing was available at the time of printing, reducing the options for new prototypes. The quality of the Arduino attachments was also not advantageous because of their large size and faultiness at times. A challenge faced when producing the prototypes was the underestimation of the work that went into creating one. Only two prototypes were achieved because of this. In addition, the sensory feedback being external to the prototypes was a limitation.

Future Research

Future work on this project will be geared toward implementing permanent electrode sensors/sensory feedback systems while continuing to improve upon the criteria. An overhaul of the sensory feedback system will lower the abandonment rate of the prosthesis, add to the control the user has over the prosthesis, and make the whole system a better overall experience. In addition, because of the 3D printing filament limitations, more materials, such as carbon fiber, should be implemented in the future. Carbon fiber or other materials could make the prosthesis lighter and easier to carry around all day for the user.

Section V: Conclusion

Objectives

Going into this endeavor the specific aims for the modular prosthesis were: functionality, modularity, durability, comfort, and cost-effectiveness.

A prosthesis lacking functionality has no use. There were three main trials to test the functionality of the prosthesis. The three main trials are stacking wooden blocks, hanging clothespins, and twisting a round doorknob with the prosthesis prototype.

Modularity is what will allow the prosthesis to grow up with the children. As the residual limb of the child grows, so too will the prosthesis. Modularity can be achieved in many different ways, a few of which are: modular plastic 3D-printed pieces that attach, airbags and an air pump that will adjust the size of the prosthesis, or a combination of the two.

If the prosthesis is not durable, the user has to adjust their life to the prosthesis when it should be the other way around. The lack of being durable could ultimately lead to prosthesis abandonment, lowering the user’s quality of life. The user must be able to trust the prosthesis, and for that to happen, it must be durable and sturdy. Many different types of 3D-printing filaments at different infill levels will be tested in the creation of this prosthesis.

One of the leading reasons for prosthetic abandonment is comfort. The prosthesis cannot be too heavy, rigid, hot, or bulky. The material used and the overall mechanical design for the prosthesis will determine these factors. Again, many different types of 3D-printing filaments at different infill levels will be tested in the creation of this prosthesis.

Emphasized throughout this project, cost is one of the main hindrances of prostheses being widely available for both adults and children. Although the budget for this project is 2000 USD, the majority of that is not anticipated to be used. In addition, 2000 USD is only a fraction of the cost of current prostheses.

Methods

To achieve these five specific aims, trials were created to test for each one. They were as follows.

Functionality — record the time it takes to stack 10 blocks, how many door open-closes in 2 minutes, and how many clothespins hung in 2 minutes for the prototype

Modularity — test for functionality at different sizes of the prototype

Durability — stress analysis on Solidworks and everyday degradation of the prototype

Comfort — weight and rigid points on the design of the prototype

Cost-effectiveness — aggregate the costs of the prototype

Results

The results of these tests for the baseline, human arm, and both prototypes are below.

Baseline — score of 266/640 in the context of this project through the engineering design matrix

Human Arm — score of 550/640 in the context of this project through the engineering design matrix

Prototype 1 — score of 446/640 in the context of this project through the engineering design matrix

Prototype 2 — score of 464/640 in the context of this project through the engineering design matrix

Along with the engineering design matrix and the trials for the five specific aims, statistical tests were also conducted on and between the mean values for each of the functionality trials. A standard t-test was performed on the functionality trials between prototypes one and two. All three resulted in p-values less than 0.05. Trial 1 (blocks) had a p-value of 0.02845, trial 2 (doors) had a p-value of 0.01621, and trial 3 (clothespins) had a p-value of 0.00431. A one-way ANOVA test was performed on the functionality trials between all prototypes, baselines, and the human arm. All three resulted in p-values less than 0.05. Trial 1 (blocks) had a p-value of 0.00599, trial 2 (doors) had a p-value of 0.0000000265, and trial 3 (clothespins) had a p-value of 0.000000017. These results give way for an additional statistic: the post hoc test.

A post hoc test was performed comparing the variance for the functionality trials between all prototypes, baselines, and the human arm. Trial 1 (blocks) had one p-value under 0.05: the baseline vs. prototype 2 with a p-value of 0.046. Trial 2 (doors) had all p-values under 0.05. Trial 3 (clothespins) had four p-values under 0.05: the baseline vs. a human arm (0.001), the baseline vs. prototype 1 (0.008), a human arm vs. prototype 1 (0.001), and a human arm vs. prototype 2 (0.001).

Analysis

Through testing for the 5 specific aims and analyzing the data, it can be confidently stated that the objectives for this project were achieved. A functional, modular, durable, comfortable, and cost-effective prosthesis was prototyped. There was statistical significance between the first and second prototypes as well as between the baseline and both prototypes ($p<0.05$ for all cases). Through the design matrices, the second prototype was determined to be the best. Further analysis of the functionality trials shows that the second prototype performs at 42% of the rate a normal human arm would. The statistical tests also point to this conclusion.

This project introduces a new, modular type of myoelectric prosthesis with bidirectional signaling. It contains many parts of previous work in the field, taking inspiration from the experiments by Zhu et al. in 2022. Some limitations were: the quality of the 3D printing, the quality of the Arduino attachments, underestimating the time it would take to design a prototype, and the external sensory feedback.

Future work will be implementing permanent electrode sensors/sensory feedback systems, continuing to improve upon the criteria, and trying new prosthesis materials, such as carbon fiber.

To conclude, a modular below-elbow prosthesis with bidirectional signaling is attainable and will allow children to grow up with and utilize prostheses better.

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Section VII: Appendices

Appendix A: Prosthesis Terminology

The term “prosthetics” refers to the field of research and expertise in designing and building artificial limbs. The term can also be used as an adjective (e.g. prosthetic limbs). The term “prosthesis” is the most accurate term for an artificial device that is built to replace a missing body part. The plural of prosthesis is prostheses (Amputee Coalition, n.d.).

Appendix B: Engineering Design Matrix

Engineering Design Matrix

Criteria (Rank)	Example	Design A	Design B	Design C	…
Safety - how safe the user feels when using the prosthesis; how well the user trusts the prosthesis (10)	9				
Functionality - determined from functionality	7				

methodology (9)					
Modularity - determined from modularity methodology (9)	5				
Comfort - determined from comfort methodology (7)	10				
Durability - determined from durability methodology (7)	3				
Cost-effectiveness - determined from cost-effectiveness methodology (6)	6				
Control - how well the user can manipulate the prosthesis to do desired actions (8)	9				
Sensory Feedback - how well the prosthesis conveys the sense of touch to the user (8)	3				
Total (Max 640)	421				

Each criteria is given a 1-10 score, then multiplied by the rank and aggregate the results to calculate the final score. Max final score is 640. This table will be used to determine the best prototype/design.

- Safety (10) - in any trials, products, or experiments involving humans, safety is always the number one priority.
- Functionality (9) - Being one of the most important specific aims of this project, the functionality of the prosthesis determines to the user if they can use the device or not. If they cannot use the product, then the product is a failure.
- Modularity (9) - Modularity is one of the features that makes this prosthesis design unique and separate from the rest of the field. If the prosthesis is not modular, then it is just like all of the other competition in the field. The project will then be considered incomplete.
- Confort (7) - Comfort is one of the leading factors in prosthesis abandonment, so if the prosthesis is not comfortable for the user then it will be deemed unusable.
- Durability (7) - If the prosthesis is not durable, especially considering the target group of children, then the product will be rendered unusable for most of the time and cost the user extra money.
- Cost-effectiveness (6) - The price of prostheses is what keeps them from being available to a large proportion of the global amputee population, especially children. Being one of the specific aims of this project, price plays a factor, but is not as important as the others in this prototyping stage.
- Control (8) - If the user cannot control the prosthesis, they would most likely abandon it. Going hand in

hand with functionality, the prosthesis must be controllable.

- Sensory Feedback (8) - Sensory feedback, in conjunction with control and functionality, plays an important role in the abandonment of prostheses. The prosthesis must have sensory feedback, no matter what kind.