Michigan Neuroprosthetics Design Team Independent Research

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Abstract Michigan Neuroprosthetics Design Team strives to develop cost effective, 3D printed, transradial arm prostheses. Our clients are children who cannot afford to invest in a neurologically controlled prosthesis that will be quickly outgrown. As a member of the mechanical subteam, I am responsible for designing the arm in Fusion 360. The design goals for the 2020 design cycle were to reduce the weight of the forearm, separate the battery compartment for simplified charging, redesign the string channels in the palm to reduce tangling, and perform mechanical testing to address design weaknesses. These goals, along with additional design changes, were met with the exception of physical mechanical testing. COVID-19 prohibited in-person meeting, so Finite Element Analysis (FEA) testing was performed instead.

***Index Terms*— 3D Printing, prosthetics, CAD modeling, socially engaged design**

I. INTRODUCTION

An estimated 1 in 2,500 children is born with an upper limb reduction defect [1]. Given that a child grows rapidly and would need a replacement prosthesis every 1-2 years, this results in a prohibitively expensive lifetime cost. Advances in additive manufacturing technology have expanded the possibility to produce custom 3D printed prostheses, and organizations such as e-Nable have formed to design body-powered hand prostheses that can be printed at home [2]. However, standard pediatric body powered prosthetics have an average rejection rate of 45% [3]. Common complaints center around the weight and comfort of the prosthesis, and many patients feel more capable with one hand alone rather than using a prosthetic device. Electric powered prosthetics have a statistically significant lower rate of rejection (p=0.002) among pediatric patients [3]. The problem is that advanced electric powered prosthetics can cost $5,000 - $50,000 [2]. Therefore, Michigan Neuroprosthetics Design Team has identified a need for a cost effective, electric, pediatric prosthesis.

Michigan Neuroprosthetics Design Team is a student run organization that designs and manufactures neurologically controlled, transradial arm prostheses. The organization employs 3D manufacturing to keep costs low, and they provide arms directly to clients free of cost. The organization was inspired by e-Nable, but we set out to make an electric powered model instead of the body powered design that required wrist flexion to produce grip.

Myoelectric prosthetics are the most accessible form of electric powered prosthetics. They use muscle contractions as the method of controlling arm activity. Muscle contractions are regulated by action potentials from neurons, which result in rapid depolarization of the muscle cell membrane [4]. This electrical impulse is significant enough to be detected on the skin with surface electrodes. For upper limb prosthetics, a pair of electrodes are placed on the bicep to isolate the desired muscle signal by differential filtering to remove noise, and a ground electrode is placed on the elbow.

The forearm of the prosthesis houses two servo motors that are connected to strings that run to the ends of the fingers. Activating the motors tightens the set of strings on the front of the fingers while loosening the back set in order the contract the fingers. The user controls hand motions by contracting his/her bicep, where electrodes detect the electrical impulses and send them to a circuit board that controls the motors. One motor drives the thumb and index finger separately from the other three fingers for greater control of gestures. A rechargeable battery powers the arm.

Michigan Neuroprosthetics resides in a market niche between simple, low-function prosthetics like e-Nable’s designs, and advanced powered hands such as the Bebionic hand from Ottobock and Hero arm from Open Bionics. This unique role leaves room for substantial growth as the organization improves existing designs and expands its offerings.

The team has been working with a client for two years to get feedback on prototypes. A previous prototype was delivered in 2020, so feedback on this prototype was used to establish the design goals for the 2020 design cycle. The client complained that the arm was too heavy which made it cumbersome to wear for a full day. He also requested improving the appearance of the arm by removing a bulge on the forearm that was used to store electronic components. Finally, his mother asked for a way to charge the device without having to disassemble the forearm and remove the battery. As the team works towards open sourcing the prosthetic arm, an additional design improvement was suggested to improve ease of assembly: the channels in the palm should be redesigned to make stringing the hand simpler.

The previous model files were not managed with good modeling practices, so this year all designs were made from scratch. An emphasis on good modeling practices was maintained so that it will be easy to update existing files with improvements in future years. Additionally, as the team seeks to open-source its designs, it is important to be able to quickly scale the design to fit a variety of patients. Therefore, parametric modeling practices were used to define model dimensions with a few parameters that can be rapidly adjusted.

II. MATERIALS AND METHODS

All design work was completed using Autodesk Fusion 360. The organic form of the arm was made in the Sculpt environment and the underlying sculpted form was maintained from the previous year.

A. Palm

My first task was to remodel the palm from scratch with attention to feature dependencies. The previous model had become cumbersome to update because changing one section of the design often caused unpredictable changes on other features due to poor dimensioning techniques. Another focus of the new design was organizing the feature timeline in Fusion 360 so that it would be easy to locate specific toolpaths and modify them in the future.

The largest aesthetic change made to the palm was smoothing the knuckle joint region. The previous model was a blocky set of cuts that emphasized functionality over appearance. In the new model, all fingers are spaced regularly and dimensioned with respect to the common shaft that holds the fingers in place. Fillets were then used to smooth over any remaining sharp edges.

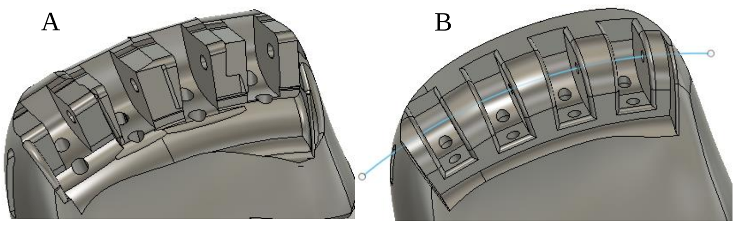

Fig. 1. (A) Previous knuckle design, (B) Updated design showing the centerline for the joints

In order to address difficulties stringing the palm, the channels were redesigned. The channels were created using the loft command to cut a path along a centerline from the holes in the knuckle joints to the central hole in the palm. The new centerlines consist of 3D splines which enable more design freedom than the previous planar and linear method. As a result, the centerlines now intersect much lower in the palm. It was important to remove the ledge seen in the old design in order to provide a smooth transition and eliminate corners that could cause the strings to fray. Additionally, the previous channels for the thumb strings made a sharp transition into the main palm cavity which could lead to additional wear on the strings when transitioning between the open and closed state. I added a chamfer to the exit of this channel with the goal of reducing frictional forces.

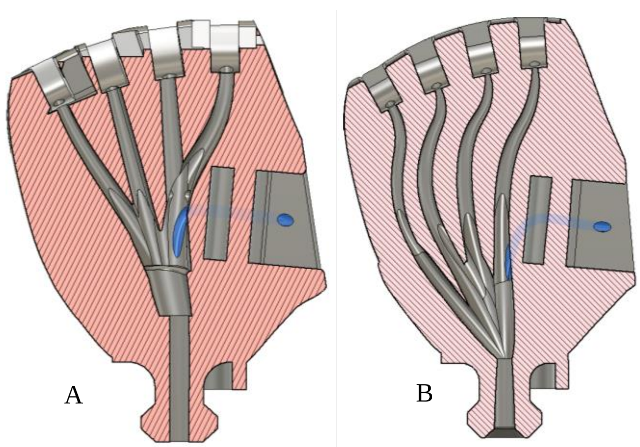

Fig. 2. Cross sectional comparison of string channel designs with thumb channel in blue. (A) Old design, (B) updated design

B. Fingers

While redesigning the string channels in the palm, the channels in the fingers were also evaluated. The previous channels had sharper turns than necessary and thin walls between channels. Additionally, the channels exited straight out the bottom of the finger, so that when the finger rotates, the string is pinched in the joint. The channels were recreated to better optimize the space and reduce sharp turns, and they were extended so the joint could rotate without resistance. Another improvement that was made to the fingers was adding counterbores to the tips of the fingers. The ends of the string are knotted so that they do not slip down the channels, but previously the knots sat of the outside of the fingertip. Now the knots can be concealed within the finger itself.

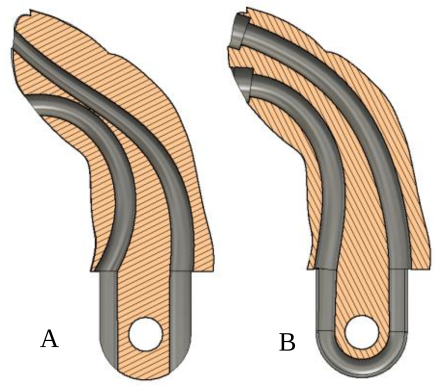

Fig. 3. Cross sectional comparison of string channel designs in the index finger. (A) Old design, (B) updated design

C. Forearm

Our client's largest complaints related to the design of the forearm. The model was bulky and heavy which made it cumbersome to wear all day. Even though the arm is manufactured by 3D printing, the old design used subtractive instead of additive design methods. This means that the design started with a solid forearm and cavities were carved for each of the components, as seen in Figure 3. Not only does this waste a lot of material, but it makes wire management quite difficult. Consequently, a large bulge was added to the lid last year in order to accommodate the circuit board and wires. This dramatically reduced the realism and aesthetic appeal of the arm.

This time, the shell command was used to start with a hollow forearm. Mounts were designed additively to anchor the components. Since the motors are no longer supported in cavities, four screws instead of two were used to secure each motor. Heat set threaded inserts were used instead of screwing directly into the plastic. In order to optimize space efficiency, the proximal motor was turned sideways. A test bench was constructed to test this novel configuration and preliminary tests indicated that it did not negatively affect actuation of the hand. However, the sideways motor resulted in additional assembly challenges, as the securement screws were hard to access. Thus, the lid was adjusted so that the motor could be directly accessed. This modification can be seen in Figure 5.

The battery was confined to its own slot near the back of the forearm. The location of the battery was maintained from the previous design because its proximity to the elbow reduces the torque produced by the weight of the battery.

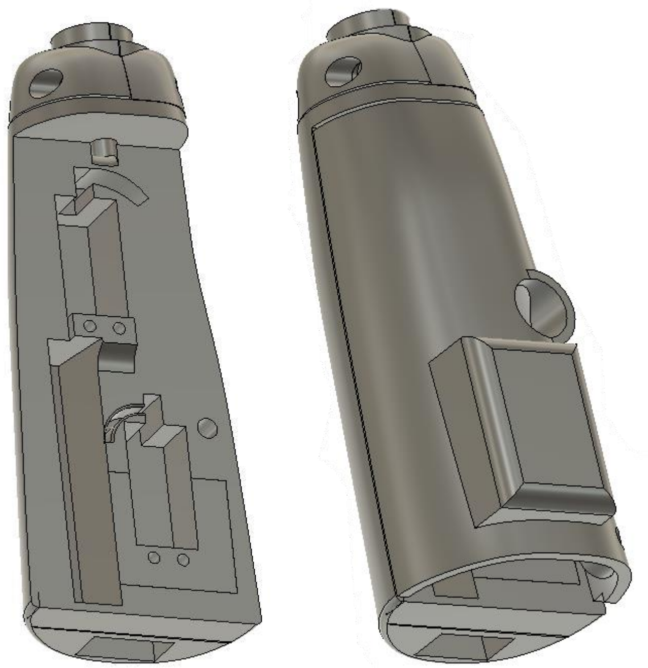

Fig. 4. Previous forearm design with and without lid. A bulge was added to the lid as a last-minute design change to accommodate wires. The circular cavity in the lid housed the power switch.

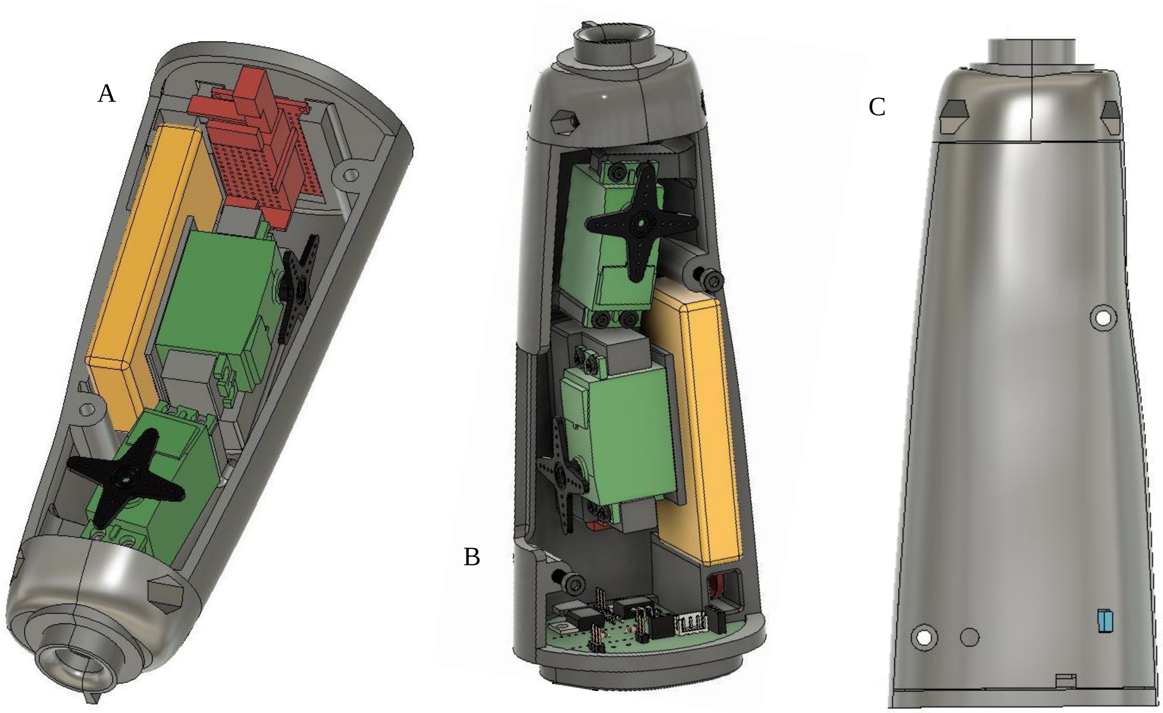

Fig. 5. Intermediate (A) and final (B) forearm design with electrical components. The power switch is attached to the inside of the final lid design (C) and can be seen in blue.

In order to improve the wire management of the forearm, the mechanical subteam worked closely with the electrical subteam to model the electrical components. Accurate models of the circuit board and voltage regulator ensured all components would fit when the physical prototype was created. Previously, a bulky protoboard design was used for the main circuit board, but the mechanical and electrical subteams collaborated to design a space-optimized printed circuit board (PCB). We wanted the board to fit at the back of the forearm and be as thin as possible, so the PCB was made in the shape of a circle with a notch to accommodate the battery charging port. This unique shape fits perfectly in a cavity with a few thin brackets preventing the PCB from shifting forward. With all the additional space in the forearm, the bulge was able to be removed from the lid.

After the removal of the bulge on the lid, there were concerns that the power switch could inadvertently get toggled by getting bumped. Therefore, a new button that was smaller and operated via slide instead of toggle was selected in cooperation with the electrical subteam.

Another complaint was that the process for charging the battery was not user-friendly. Every evening, our client, with the help of his mother, would have to unscrew the lid and remove the battery to charge it. He would then have to reconnect the wires in the morning and force the messy wires back under the lid. In order to improve the user experience of the device, a slot was added for access to the battery charging wire without having to remove the lid. A plastic plug covers the hole and prevents the charging wire from hanging out of the arm during normal use. One challenge faced was that the intermediate design used a square plug ordered from McMaster-Carr, which was not as deformable as expected and could not fit in the hole. Consequently, the plug cavity was redesigned after researching new plug options. The resulting design features a depression for easy removal of the plug, which can be seen in Figure 6.

Fig. 6. Final plug design for battery charging port

Since the internal components of the forearm do not need to be regularly accessed, two screws instead of one now secure the lid. In the previous design cycle, assembly components were not considered until the prototype was constructed. Consequently, the screws selected were not always the best fit. This year, all materials except for the plug were selected from McMaster-Carr. The bill of materials for the forearm is available below.

TABLE I
PARTS LIST

Part Name	**Qty**	**Description**	**Material**
Case	1	-	PCTG
Lid	1	-	PCTG
Wrist	1	-	PCTG
Motor	2	TGY4409MD Servo Motor	-
Battery	1	500mAh 7.6V Lipo Battery	-
Circuit Board	1	-	-
Power Switch	1	0.5A 50V DC Slide Switch	-
Plug	1	PIP0688RD1	PE
Heat-Set Threaded Insert	8	94459A120	Brass
M4 x 40mm Screw	4	91290A174	Alloy Steel
M2 x 6mm Screw	8	93070A276	Alloy Steel
No. 2 Washer	8	90107A003	316 Stainless Steel

D. Forearm-Socket Interface

The previous prototype broke at the interface between the forearm and the socket after falling off the client's shelf. In order to strengthen this joint, the bottom face of the forearm case was extended from a semi-circle to a full circle which provided more surface area for epoxy. Additionally, the peg connecting the two parts was redesigned from the existing rectangle design. Fusion 360's Simulation environment was used to perform Finite Element Analysis (FEA) testing on various peg designs under a bending load. Several team members supplied designs, but I was responsible for compiling them and performing the tests.

The forearm and socket were isolated from the rest of the arm assembly and all features were removed from the inside of the forearm to simplify computation. Both bodies were defined with preset ABS plastic material properties. The assembly was constrained with a pin support at the elbow joint and a roller constraint at the wrist. The constrains were chosen to fully support the model without over-constraining it. All surface contacts between the forearm and the socket were defined as frictionless. A 200 N load was applied vertically at the interface. The average mesh size was 3% of the model size with parabolic element order.

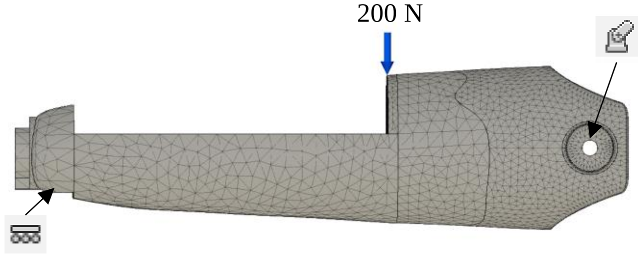

Fig. 7. FEA setup for testing peg designs under three-point bending load

III. RESULTS

The palm was successfully recreated with a noticeably smoother knuckle region. Changing the channels in the palm greatly improved the ease of stringing the hand. The thumb string channels could be further improved by additional reduction of sharp angles. Additionally, the redesign of the finger channels greatly reduced the frictional resistance to gripping, which should improve the efficiency of the motors.

The new forearm design successfully reduced the weight of the arm. When printing with a 20% infill, the old design requires 166.82g of PLA while the new design uses 153.73g. Unfortunately, we were not able to take quantitative measurements in person to validate the theoretical weight reduction, however when we delivered the prototype to our client, he expressed that it felt more comfortable. The additional free space in the forearm greatly improved wire management and all electronics now fit with the lid closed. The preliminary prototype reveals that the new power switch can be toggled by a user but is not easily accidentally changed upon contact with a flat surface.

The added channel in the forearm next to the battery successfully enables access to the battery charging wire without opening the lid. The wire can be extended out of the arm to reach the charger; however, the charger is not able to rest flush on the table while plugged in. This does not prevent use of this feature, as propping the charger on a book or similar stand eliminates the problem. Future improvements could improve the reach of the wire, or a stand could be designed to hold the charger at the optimal orientation.

A. FEA Results

I hypothesized that the failure mode of the socket separating from the forearm resulted from crack propagation originating at the external rim of the forearm-socket interface. Therefore, the design that minimized stresses at the external rim should be chosen. When comparing designs, using several smaller pegs appeared to increase the stress concentrations at this exterior surface of the interface. The ring design did appear to largely reduce concentrations at the surface. While the inner peg on this design bore a lot of stress, I do not believe that those stress concentrations would result in the failure of the socket separating from the forearm. Therefore, the chosen peg design was the ring with a larger diameter inner peg.

For all designs, the max observed stress was at the corner of the forearm, not at the interface itself. Since failure had previously been observed at the interface, this indicates that all designs reduce the chance of this failure mode recurring.

Further analysis including physical testing should be performed to support the findings of this series of FEA tests, as there is currently no rationale for the magnitude of the applied load, and several factors including surface contact definitions and the tolerances between the pegs and the holes may have oversized effect on results.

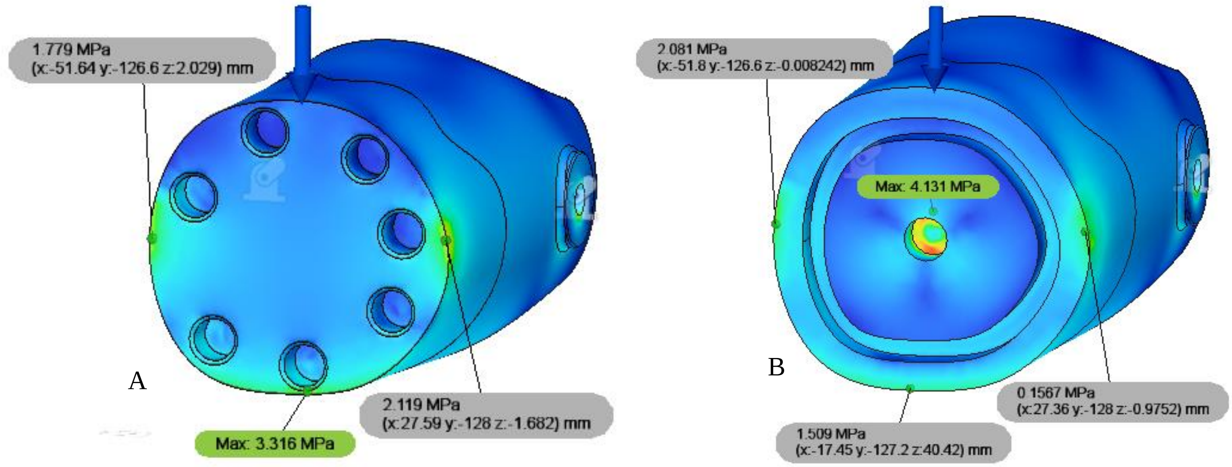

Fig. 8. Resulting stresses from the comparative FEA study on the prosthesis socket-forearm interface. (A) Example of a design with many small pegs, (B) Ring design

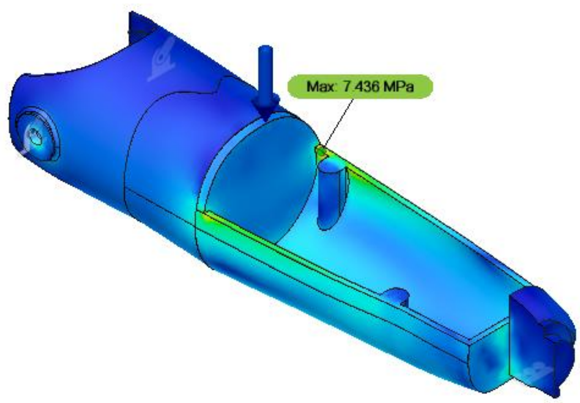

Fig. 9. Example of surface stress results from the FEA study

IV. Conclusion

Michigan Neuroprosthetics is a relatively young design team that focused primarily on arriving at a functioning prototype in previous years. Throughout this design cycle the team remained with the same client and made improvements to the existing design to improve the user experience of the device. The updates made to the hand and forearm improve the appearance of the prosthesis and lend it a more polished and professional look. The reduction in prosthesis weight increases the comfortability of all-day use. The design goal that the arm should be rechargeable without opening the main forearm compartment was met. Redesign of the string channels should result in improved grip strength and a lower chance of string entanglement during operation of the prosthesis. Ease of assembly of the arm was also improved by refining the string channels.

No baseline is available to compare the strength of the forearm-socket interface before and after design changes, however the changes made are predicted to strengthen this joint. FEA simulations indicate that the point of highest stress is separate from the interface, which supports the hypothesis that extending the back face of the forearm and redesigning the pegs reduced the likelihood of failure occurring at this interface.

Due to COVID-19, the team was unable to manufacture a prototype for testing purposes or access equipment for physical testing. However, we were able to use an off-site 3D printing farm to produce a model that we delivered to our client in late November. We will continue to receive user testing feedback on a delayed timeline. Several physical tests are planned and will be executed when we are able to return to an in-person mode. A test will be performed to assess if the new motor orientation affects actuation of the hand. The grip strength will also be tested and compared to normal anatomical strength in a comparative study. Finally, mechanical tests will be performed to corroborate the FEA simulations.

Future design improvements include further reducing the weight of the arm. The socket and triceps cuff could be refined to meet this goal. Another future goal is to add adaptive tensioning to the strings, because over time the strings loosen and need to be reknotted – a time consuming process. In the long term, Michigan Neuroprosthetics would like to expand its design offerings to serve patients with transhumeral amputations or congenital defects.

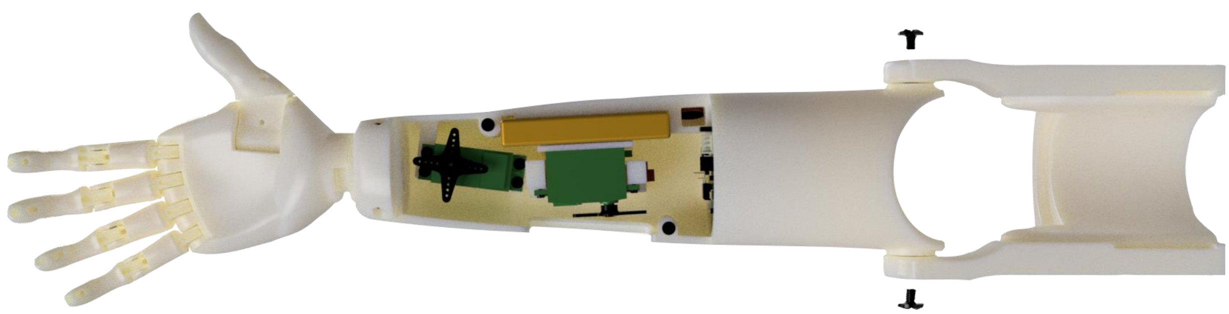

Fig. 10. Complete final assembly for the 2020 design cycle

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Allison Wilcox is an undergraduate student at the University of Michigan College of Engineering. She is pursuing a bachelor's degree in biomedical engineering with a mechanical concentration. She has participated on the Michigan Neuroprosthetics Design Team since fall '17 and was the mechanical subteam leader for summer and fall '20. She intends to enter the medical product development industry after graduation and is grateful for the experiences gained from Michigan Neuroprosthetics.