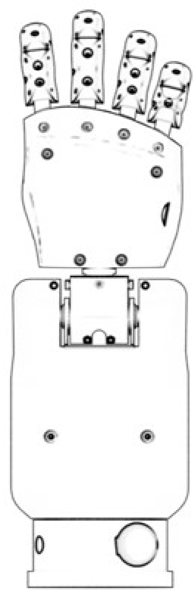
Cybathlon Report
Build, test and adapt last semesters anthropomorphic prosthesis



Leon Kiesgen *M.Sc. Robotics, Cognition, Intelligence*
03683583
leon.kiesgen@tum.de

Johannes Frey *M.Sc. Robotics, Cognition, Intelligence*
03744326
johannes.frey@tum.de

Rafael Fernández *M.Sc. Computer Science*
03753769
rafael.fernandez@tum.de

March 2022

Contents

1 Introduction

This report presents the process and development of prototyping a robotic hand. Our goal was to realize an anthropomorphic prosthesis hand design, developed in the previous semester. As patient acceptance is one of the most imported requirements when developing a prosthetic hand, our goal was not only to build a fully functioning three DOF hand, but focus on a visually appealing, anthropomorphic hand design.
In the following chapter, we want to explain the prototyping process of the highly integrated underactuated prophetic hand. We will address the leaf spring finger model, the palm design as well as the wrist and the stump interface connector. In total, we are using 3 BLDC motors with a harmonic drive with a 1:100 reduction ratio. Two motors are responsible for flexion and extension, pronation and supination of the wrist and one motor is placed in the palm and yields as an actuator for all five fingers. With a clever tendon routing, we concurrently enabled 2 grasping modes and shape adaptability, while providing improved grasping strength. For further details, consider reading the report from last semester [2].

2 Task description

During the last semester, our team developed a new prosthesis for the Cybathlon competition while focusing on an anthropomorphic look and the use of only three motors to achieve the two most important grasps (pinch and power grasp) (see report [2]).

While some small prototypes of components have been built last semester already to test different functions, the design was still mostly done virtually without building an actual prosthesis prototype. As a consequence, this semester was now used to manufacture such a prototype while improving the design by observing possible drawbacks and finding new solutions.

3 Iterative Design

The process of prototyping the prosthesis started out by reviewing our design from last semester. Then we manufactured its sub-components and improved functions and designs were needed. In case our intended designs did not work, various prototyping iteration loops used until the requirements are satisfied.

This so-called iterative design is a design methodology based on a cyclic process of prototyping, testing, analyzing, and refining a product or process. Based on the results of testing the most recent iteration of a design, changes and refinements are made. This process is intended to ultimately improve the quality and functionality of a design.

As the timeframe was limited to one semester, it was very beneficial to use rapid prototyping methods like 3d printing or SLA printing. Other norm parts like screws and ball bearings were selected based on our previous design and aggregated into an ordering list. The content of the list can be found here [file: "./Additional Material/PartList_Cybathlon.xlsx"]

4 Design changes — Prototyping

In the course of this sections, we will explore the different design changes that had to be made, in order to build a manufacturable, cost-efficient and working prototype. We will present all alteration to the original design and go into detail, why those changes were necessary. Furthermore, we are going to mention additional useful observations that we had during the prototyping process.

In Figure 1 we can see an overview of the final prototype, highlighting each subcomponent.

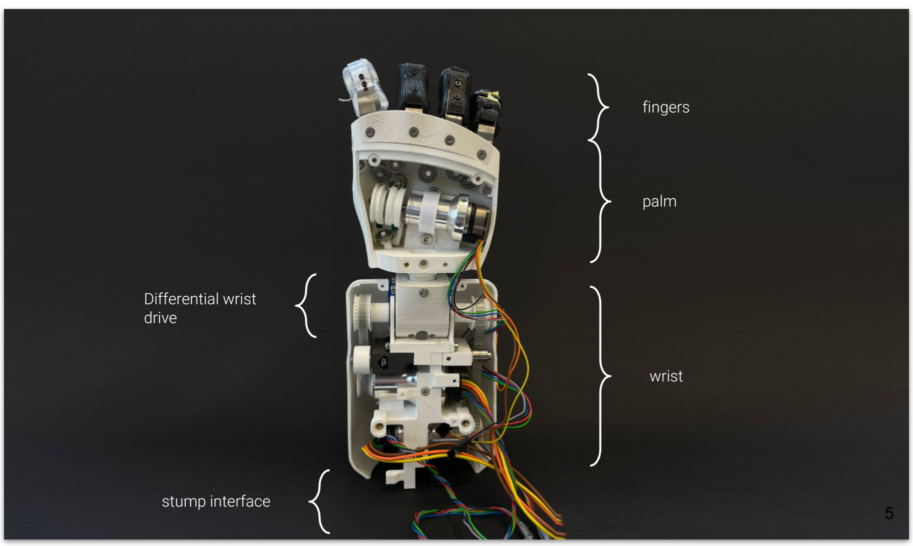


Figure 1: Bird's eye view of the final prototype. The palm lid and one side of the hull are dismantled to give a better insight into the arrangement of sub-components. Note that the sump interface is not depicted in this picture. For a detailed understanding see Section 4.5

4.1 Fingers

The prototyping process of the fingers started with the fabrication of the index-finger as an exemplary average sized finger that includes all implemented functions. As the sub-components of the finger and especially the finger tendon pulleys are very tiny, a precise but still rapid fabrication process was needed and found with SLA printing. The SLA components were then supplemented by the metal (brass) pulleys and axis that were already made on a lathe last semester for first experiments.

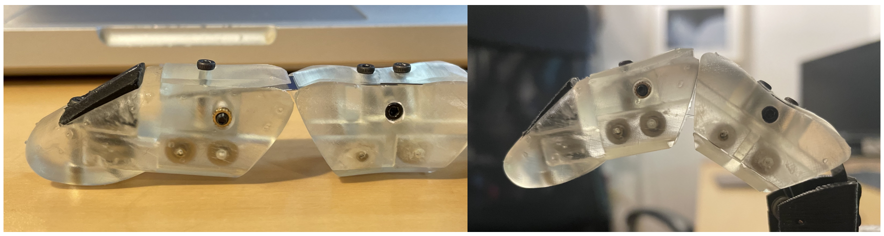


Figure 2: Left image shows the index-finger made from SLA printed parts and metal components. Right image shows the finger under load.

Some quick experiments with the first made index-finger showed that the finger function is given like expected and that the choice of size and components (such as leaf spring dimensions) fit well. Besides this, it was an interesting finding that the transparent SLA material greatly simplifies the assembly of the finger, as the tendon and pulleys were visible from outside. This way it could be observed how well the tendon in guided by the pulleys and if any of them get stuck during actuation.

Based on the index-finger experiences, one small design change regarded the bottom side of the fingers, which were now designed more round to better meet the anthropomorphic look. Besides that, some improvement was done to the fingertip, where the fingertip lid (Element_2_Tip_Lid.SLDPRT) was decreased in size mounted differently to allow more extra space in the fingertip. Unfortunately, while prototyping it also turned out that the change of the fingertip design did not allow inserting the fingertip pulley from the fingertip lid hole any longer but had to be inserted from the side of the finger, making the assembly more challenging. As this drawback was found not earlier than in assembly, it was not changed yet. The reason for this was also that the tactile sensor group developed another fingertip redesign that better meets their space requirements, which is why our solution was only temporary anyway.

Furthermore, the tendon routing was slightly changed in the first finger element (the finger elements that is closer to the palm). While in the original design the tendon was guided over the upper side of both pulleys in this finger element, it is now guided over the first pulley but underneath the second one. The reason for this is that otherwise the tendon might be able to leave the pulleys if there is not enough tension in the system (if the fingers are close to their resting position). To enable this new routing, the design in the finger element had to be adjusted slightly. This adjustment was completed by an adjustment of the axis mounting, which now makes the use of additional sleeves unnecessary, reducing the number of parts.

We could observe that it is very important to always have some tension on the tendon because otherwise it easily jumps off the pulleys. A critical point in the system is the bigger fingertip pulley, which should move freely at any time to guarantee low friction. Also, it has a large negative effect on the system if the tendon leaves one of these fingertip pulleys since this does not only increase friction dramatically but will also make the tendon jump off the small pulleys that are closest to the fingertip. The reason for this is that their position is fixed and the distance between the tendon forward and backward path decreases significantly if it leaves the fingertip pulley (the diameter of the fingertip pulley is much larger than the one of its axis where the tendon jumps on). If this happens, it's challenging to get the tendon back on place, most of the time the finger had to be opened to do so. However, when the hand was completely assembled and the tendon was pre-tightened, this didn't happen frequently anymore.

For the manufacturing of the remaining four fingers, we decided to switch to FDM printing since the SLA printer was less frequently available, which would have sowed down the prototyping process. Image 3 shows some parts of the fingers and the finally assembled fingers, the thumb was made separately in the same manner. The use of non-transparent material and FDM manufacturing method for the remaining fingers made the assembly of the fingers and especially the assembly of the tendon much more challenging. The reason for this was that parts and tendon could not be observed from the outside, so it was also hard to find the right way for the tendon. Besides that, the used PLA material looked quite nice but was more flexible than the previously used material from SLA printing. Due to this, the finger elements deformed mire when tightened by screws, which resulted in bigger gaps between pars and generally less accuracy. Still, the results worked and could be used for the testing purposes they were made for.

Figure 3: Prototyping of the fingers: Left image shows the main components, right image shows assembled middle- ring- and pinky-finger.

For the needed accuracy in the tendon system, we however decided to stay with SLA printing for the tiny finger pulleys (see image 4) and used a tough (blue) material.

Unfortunately, it turned out that the blue, tough SLA printer material for

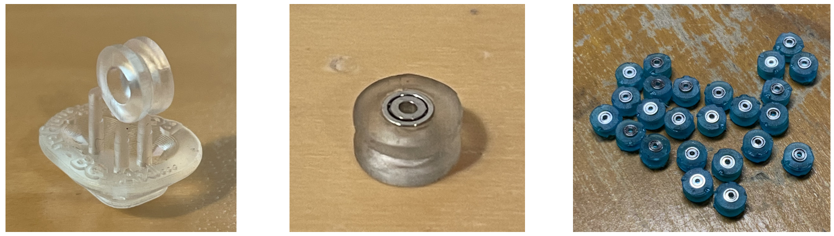


Figure 4: Finger tendon pulley made from clear SLA printing material. Left image shows the pulley with support structure after the printing, middle image shows the pulley assembled. The right image shows the pulley made from blue, tough SLA printing material (right).

the finger pulleys was actually less stiff than the original (clear) one. This did not worsen the function of the pulleys, but the ball bearings tended to move out of the pulleys more easily, which is why we recommend using the clear material for upcoming prototypes. Experiments with the actuated hand showed that the fingers close as intended, and that the leaf spring force was also high enough to open the fingers reliable.

After the assembly of all five fingers, they were connected with the palm to form the hand. For the actuation of the fingers, the tendon was installed, which was a challenging task due to the high number of pulleys and the need to keep everything under tension to prevent the tendon from jumping of the pulleys. Experimenting with the tendon showed that its diameter strongly influences the friction in the system and thus the movability of the fingers. It turned out that the thin one we bought (0.26 mm Dyneema fishing line) allowed good finger movement, while the thicker one (same material with 0.48 mm in diameter) did not work well. Another influence was the stronger coating of the thicker tendon, which again lead to more friction and made the tendon less flexible. With the thin tendon in use, it could be observed that the coupling of the fingers works as intended and that the pulleys in the fingers rotate with tendon movement.

Besides the findings that we made for the tendon system of the finger, one major observation was that the leaf spring finger joints did not provide enough torsional stiffness (see image 6). While the spring itself could handle lateral forces well, the missing torsional stiffness is much more important because when an object is grasped and lifted, this leads to a lateral force at the bottom side of the finger and thus to a torsional stress at the leaf spring. Therefore, it was found that a higher torsional stiffness is needed in order to enable good grasping performance.

To solve this issue, a solution had to be found that was easy to include, working well but also not requiring major changes in the finger design. Different concept were collected to solve this problem, including:

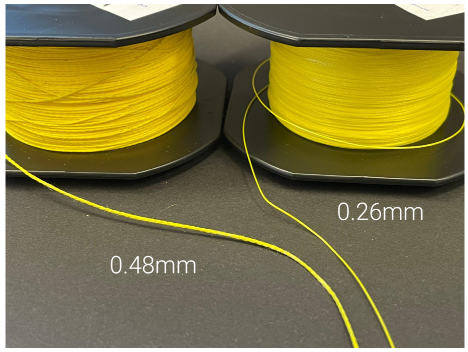


Figure 5: On the left we can see the tendon with 0.48mm in diameter on the right the 0.26mm in diameter. Both provide enough tensile strenght with a minimal safety factor of two.

- An adjusted leaf spring design that has a bigger torsional stiffness
- Intersecting finger elements that do not allow any torsion by design
- Bowden cables on the finger sides

Problems of these concepts however were mainly too much friction under load or too big manufacturing and design complexity.

This is why we developed a new idea based on flexible strings instead of rigid components. Inspired by the function of the human knee, the idea was to use cruciate ligaments in the finger joints to provide the torsion stiffness by applying only tensile force.

Implementing this idea was made possible by the fact hat the finger elements nearly meet at a single point do to their chamfered design. At this point, the elements touch each other in the prototype setup and roll on each other when the finger is bent. This means that in reality the contact point is not fixed but moves during the finger bending. However, this shift is so small that it can be neglected and the meeting point of the finger elements can thus be considered fixed. Hence, there are two fixed points for each joint, with respectively one fraction at the first finger element and one fraction at the other finger element. Using this fact, we concluded that the diagonal distance from each fixed point to the bottom side corner of the respectively other finger element must be constant to not allow any torsion in the joint. Restricting this length can simply be done by adding a string between the points – which is nothing else than a ligament. As the strings can only take tensile force, there are two strings needed for each finger element, making four connections for a joint and a cross shape – hence cruciate ligaments. As a nice side-effect, the cross shape also enables the tendon to move through the joint without any contact to the ligaments. The resulting design can be seen in figure 7. What's great about this design is that the ligaments can be made from the same material as the tendon, which reduces system complexity and integrates them well in the design. Besides that,

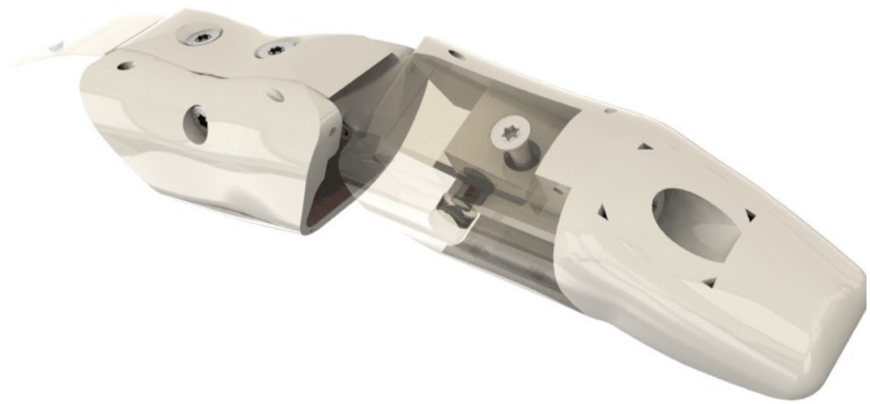


Figure 6: Possible joint rotation due to missing torsion stiffness in the finger joints.

they don't influence the intended motion of the fingers at all. Furthermore, the torsion stiffness can be adjusted via the tension on the ligaments.

To reduce complexity even more, holes were inserted in the finger that connect the anchor points of the ligaments with each other such that only two separate strings are needed for one joint.

While the cruciate ligaments were initially designed and tested for the connection of two finger elements, the system also works for the joint between the first finger element and palm. However, the interface between fingers and palm was not yet designed to match the interface between finger elements. In particular, the current design forms a gap between the palm and the first finger element. Therefore, there is no fixed point in this joint, which hinders the implementation of the cruciate ligament reinforcement. As the palm prototyping was already at an advanced stage at the time of the development of the cruciate ligaments, we decided to not change the palm design for now and instead only include the reinforcement in the finger/finger interface. If both finger joints will finally feature holes for the cruciate ligaments, the design will allow guiding two ligament strings from the second finger elements through the first one to the palm, where a tension mechanism can be implemented that will tension both joints at the same time.

Experiments with the hand furthermore showed that a bigger leaf spring length is needed to enable full bending of the first finger element. As the palm/finger interface was only defined rudimentary, the leaf spring length of the first prototypes middle- and ring-finger were chosen too small, which is why they couldn't reach their max load position.

In addition to these design changes, the CAD setup of the finger design was simplified. While all fingers existed as individual designs before, they are now condensed in one design with four different configurations, representing

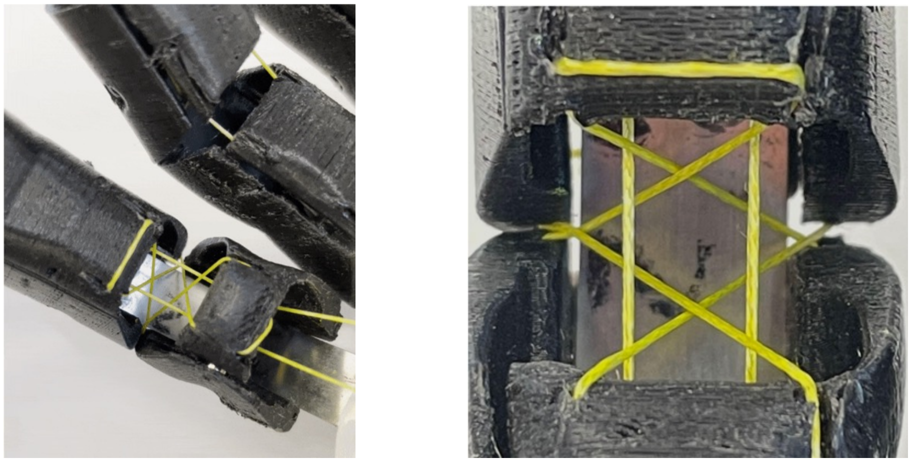


Figure 7: Cruciate ligaments installed in the finger elements joint of the pinky-finger. The parallel strings are part of the tendon, which is not intersecting with the cruciate ligaments.

the index- middle- ring and pinky-finger. This change was possible because the design of these four fingers only varies in sizes, while their main structure remains the same. Since the design of the thumb differs significantly from the design of the other fingers, this one stayed the same and thus separate.

4.2 Palm

The palm prototyping was very straightforward, as only minor changes had to be made to produce it. The main components of the palm are the palm_bottom, palm_top, palm_bottom_tendon_mount, palm_finger_mount. All of those have been FDM printed using the Prusa i3 Mk3s, with 100% infill for additional strength. In general, finding a good printing orientation for those anthropomorphic parts was tricky, as no planar surface existed. To prevent excessive post-processing, we suggest that contact surfaces are not place directly over support structures. In this case, an upward facing position yielded the best printing result. The palm_bottom part was impossible to be printed in an upright position, as additional support in between the most fragile cross-section was needed, which resulted in a lot of broken prints when removing the support. In Figure 8 we can see a picture of the palm_tendon_mount including a sketch of the tendon routing. For lager turning radii of the tendon, the 12 mm pulleys have been used, the overall reducing friction. For smaller directional changes the 6 mm pulley have been changed to steel pins (lower friction coefficient) as the assembly process of vertically orientated axes would have been prone to error. To fix the 12mm pulleys in the original design, a looking ring was used to secure them in place. However, after some experimental results they were not necessary as a press fit on the PLA axis was sufficient for fixation.

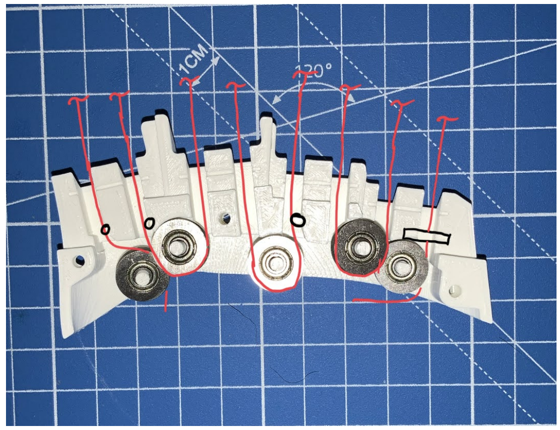


Figure 8: Picture of the palm_tendon_mount which is vertically screwed to the palm_bottom to fixate a 2 mm axis (holding two small pulleys). The 12 mm pulleys are already mounted with the tendon routing highlighted in red.

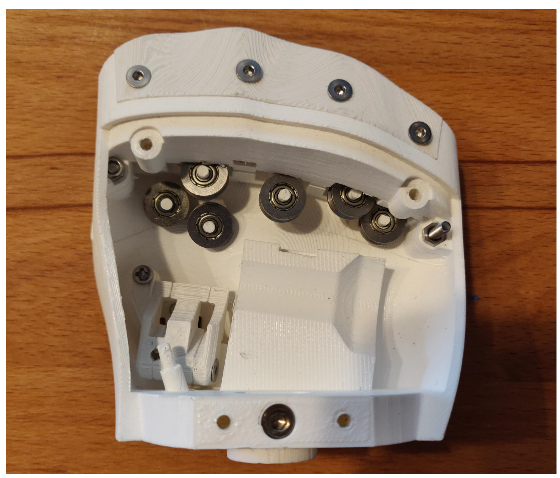


Figure 9: Fully assembled palm excluding motor unit. All parts besides the standard parts are 3D printed.

In Figure 9 we can see the fully assembled palm. By only using PLA parts, the palm is relatively light while also being very stiff. Imported to note is that only screws which regular need to be disassembled use tightening nuts or threaded insert. All other screws are self cutting, to save space.

4.3 Differential Drive

The differential wrist mechanism, is one key design choice in the wrist design that allows a light and ridged arrangement. With this coupled motor driven mechanism, it is possible to move the motor closer to the stump, which has proven to be a more pleasant experience for the patient as weight is one of the main reasons for prosthesis abandonment [3],

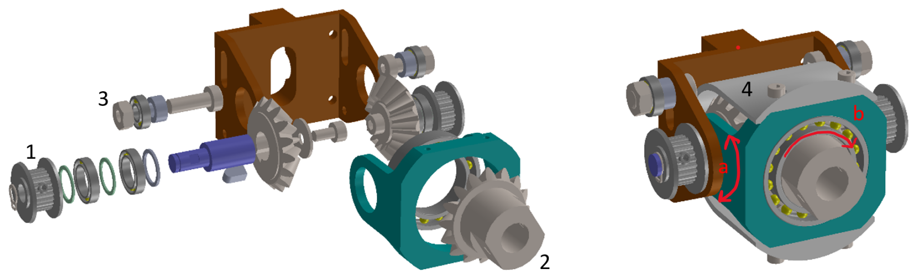


Figure 10: Explosion view of the old differential wrist design.

Throughout prototyping, we found out that the current design had some major problems which prevented us from ordering or manufacturing any parts. To name the main ones:

- lateral fixation of the ball bearings
- allen key does not fit into the gap between beveled gears
- beveled pinions were not manufacturable.

Figure 10 depicts an explosion view of the previous differential mechanism. Originally, the U-profiles were design to be CNC milled, hence the small wall thickness. To verify the design and the mechanism, we decided to redesign all part to be 3d printable. This included adding lager wall thicknesses, tolerances depending on the used printer, and new mounting points for the wrist bone. Both the U profile on the hand side and the U profile on the elbow side are mounted axially on the beveled gears and need to be able to move independently so allow for flexion and extension. Therefore, two independent ball bearings were used in the old design. The problem was that they were laterally not fixed to the u profiles, which could lead to the ball bearing slipping out. To overcome this issue, a radial friction bearing was used. The plastic to plastic articulation has low friction, low play and is easy to assemble. Another benefit is that only one radial friction bearing is needed, as both u profiles can independently rotate. This reduced the overall footprint, made a 3d printable design possible.

For testing, the bevel pinion gears were also FDM printed. This was extremely usefully as the overall mechanism could be verified without high investment. For a second prototype, it might be interesting to replace the gears with metal gears to prevent wear and tear. However, the PLA parts had a high strength and from our initial test are more than strong enough to fulfill our requirements. Throughout the development process, there were several occasions

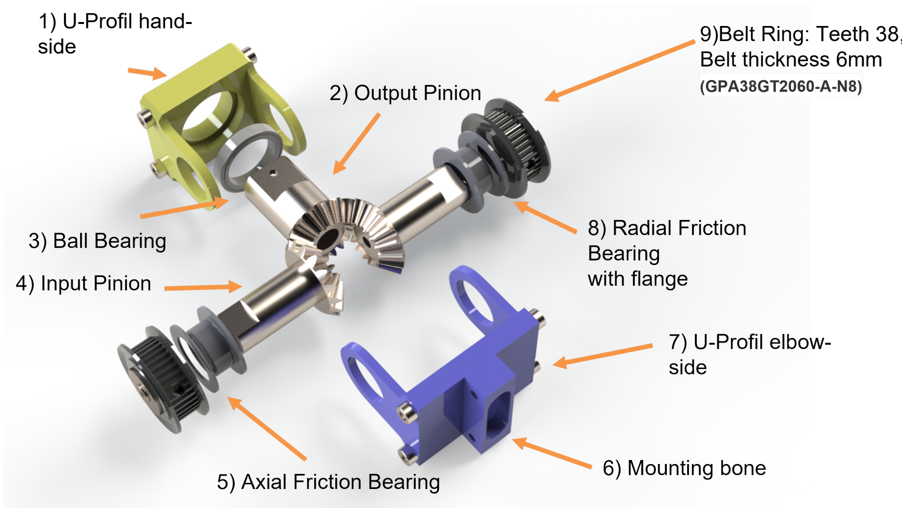


Figure 11: Exploding view of the updated differential wrist mechanism. All functionalities as well as dimensions stayed the same. However, instead of two ball bearings, the new design uses one friction bearing.

where minor parts had to be adjusted. With the rapid prototyping methods we used, it was not only easy to change some parameters, but also time and cost-efficient. To give an example. We had to adjust the diameter of the cable tunnel in the output pinion so that the motor connector could easily be feed though the cable canal. Even tho the prototype might not be mechanical as stable, it is always a best practice to verify a mechanism with cheap and fast manufacturing solution.

The motion of the differential drive is coupled and actuated by two belts connected to a motor unit in the back of the wrist. Flexion and extension can be achieved by rotating both motors in the same directions. Pronation and Supination is realized if the motors are actuated in opposing directions. With this design, a superposition of both DOF is also possible. To realize a closed loop controller design, it might be useful to have the transformation matrix of the dynamic system. Let say θ_L is the angle of the left and θ_R is the angle of the right motor. Then the resulting output angels θ_{wirst} and θ_{hand} can be describe as:

$$\begin{bmatrix} \theta_L \\ \theta_R \end{bmatrix} = \begin{bmatrix} -1 & -1 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} \theta_{hand} \\ \theta_{wrist} \end{bmatrix}$$

Note that the motor of the wrist are arranged in opposite direction, and positive movement corresponds to a counterclockwise rotation.

4.4 Wrist

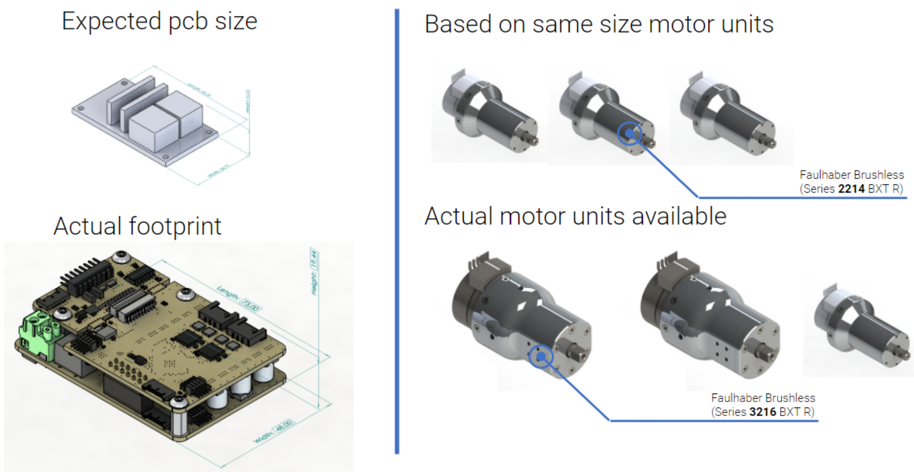
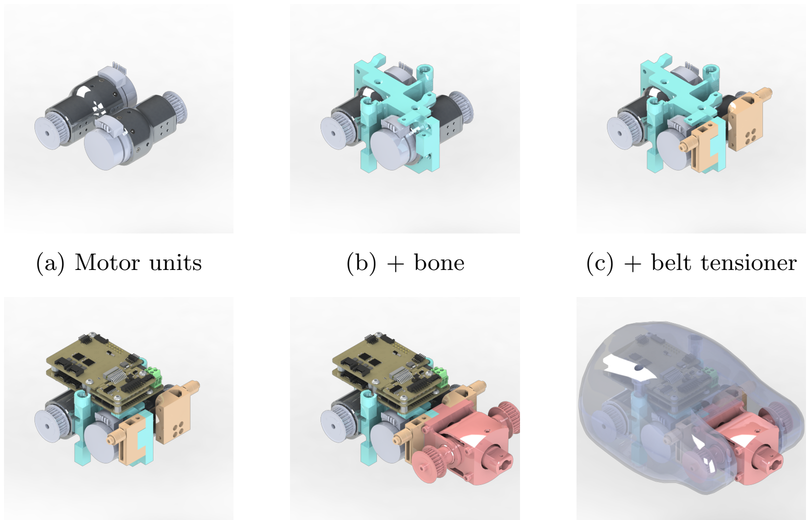


Figure 12: Visualization of the main problems that occurred during the prototyping of the wrist. On the left we can see that we hand to account for a lager PCB, nearly doubling in every dimension. On the right, we can see that the motors used in our previous design were not available in this timeframe. Therefore, we hand to switch to lager units available at the lab.

With the beginning of the semester, it already became clear that we wouldn't be able to use the motors that had been selected for the wrist last semester. Hence, we had to switch to the ones available from the old Cybathlon prosthesis. Without further prototyping, we therefore knew that a redesign of the wrist was necessary to meet the new dimensions of the motors. This was reinforced by the fact that the PCB that was developed for the prosthesis is significantly larger than we expected last semester. In total, the size of the wrist therefore had to increase in order to handle the bigger sub-components.

The design changes in the wrist started with the redesign of the bone (See Figure 13a) which holds the two wrist motors. The part was designed in such a way that the distance between the motors was minimized, which leads to the smallest possible overall length of the wrist longer wrist means bigger lever when carrying load). Figure 13a shows the updated bone design, which is now also fully 3D printable. The bone also holds the PCB, which is why there are connection points implemented in its design. As the PCB only lies on only one side of the bone, it was furthermore no longer possible to place the bone and therefore the motors in line with the differential gear while keeping the outer shell of the wrist symmetrical. Hence, the motors now lie below the differential, which also moves the wrist's center of mass downwards, away from the symmetry line of the wrist.

The movement of the wrist joint is generated using an updated differential



(a) Motor units (b) + bone (c) + belt tensioner

(d) + PCB (e) + diff drive (f) + hull

Figure 13: Overview of the main components of the wrist.

design (See red part in Figure 13e). For a more detailed description, see Section 4.3.

To connect the differential with the wrist motors, belts were used just like in the original design. Since the wrist motors are placed one after the other in the arm, different belt lengths were needed for each motor. The belt length was then chosen according to the wrist dimensions and available standard belt sizes. To get more flexibility in the belt sizes, we designed custom belt pulleys.

To tension the belts, we designed a belt tensioning mechanism (see orange part in Figure 13c) that attach to the bone. They consist out of ball bearings that are mounted in a slotted hole with a screw so that their position can be adjusted, which in turn tensions the respective belt.

After all inner components were redesigned, the hull design (Figure 13f) could be adjusted accordingly. Like in the original design, we tried to keep the hull round and as slim as possible to give it an anthropomorphic look. Part of this was also to keep the number of screws and holes low to get a nice surface. Like all other redesigned components, the hull was made completely 3D printable.

4.5 Stump interface connector

The stump interface connector is a part that joins the whole wrist assembly (wrist, palm, fingers) with the stump interface that was provided to us. Apart from that, the design of this part also allows for an additional manual degree of freedom for the wrist, thus providing more value to the final user.

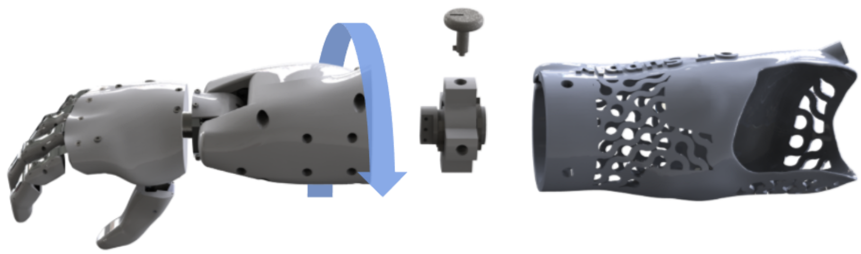


Figure 14: Wrist assembly, stump interface connector and stump interface

In the last semester design, a couple of components of the stump interface connector were designed to be made out of metal. This provided the required strength to handle to full wrist assembly weight, plus external forces applied by the user and the object being held. However the material chosen had the drawbacks of making the prototyping process slow and expensive, to a point that properly iterating on the part was not an option due to the somewhat tight deadline of a few months of semester work. Additionally, the material would significantly increase the full prosthesis weight.

Because of these reasons, in order to do some meaningful progress, the decision of redesigning the stump interface connector was made. The goal of the redesign was to be able to 3D print it with PLA and therefore iterate quickly on the prototyping process.

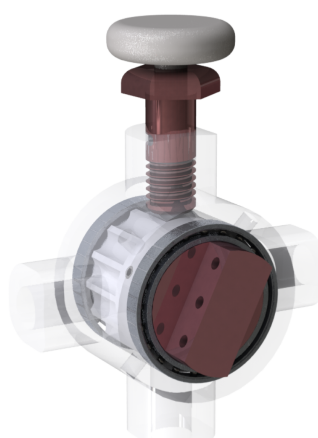


Figure 15: Previous stump interface connector design. The parts designed to be made out of metal are marked in red.

As seen in the pictures, the arm axle (arm_axle) and the radial stopper bolt (radial_stopper_bolt) were designed to be made out of metal. Thus, the designed had equivalents made out of PLA.

To achieve this, the arm axle and the ball stop ring (ball_stopring) were merged into one solid 3D printable part, the 3D arm axle (arm_axle_3d).

In the previous design, the axial translation between the stump interface outer part and the arm axle was constrained by two rotor clips. In the new design, these were replaced by 3D printed clips. In order for the new 3D printed to fit the assembly, the outer part went to some dimension adjustments and simplifications.

Finally, the fact that the assembly would be made of only PLA, made the radial stopper bolt unnecessary. Therefore, it was removed and the function of guiding the radial stopper knob (radial_stopper_knob) was provided by making a slot directly carved into the outer part. Achieving this also involved some small adjustments to the radial stopper knob.

With these three changes (Arm axle Redesign, 3D printed clips and radial bolt removal), the new stump interface connector was suitable for being a good replacement for the old design.

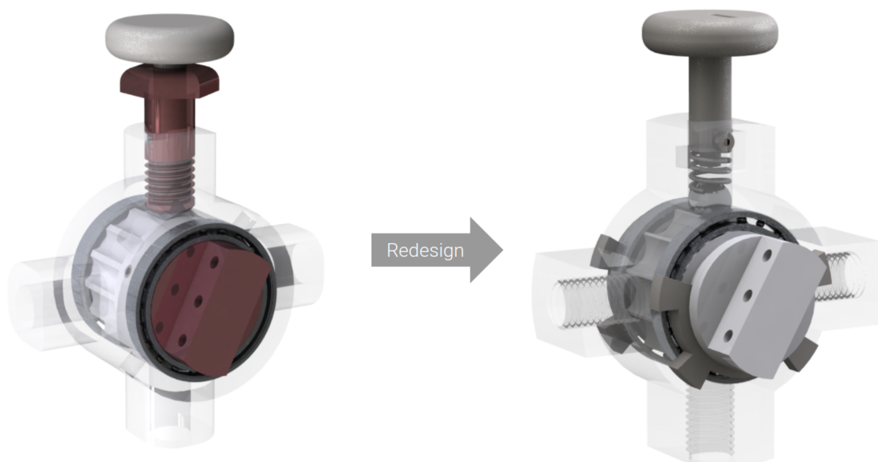


Figure 16: Side by side comparison of the old and new design.

Before going to the prototyping process, a force simulation against the 3D arm axle was performed. This part has to resist to the torque applied by the weight of the wrist assembly and the possible items being held, therefore it was crucial that the construction met the mechanical requirements. The simulation was done in SolidWorks, with a force equivalent of holding an item of 1Kg. The results shown that the internal forces of the arm axle were well beyond the ultimate tensile strength of the PLA. However, after some additional research, it was found out that due to the amount of variables that are involved in 3D printing, these kinds of simulations may have a significant margin of error, therefore, the definitive results will be seen only in the prototyping phase.

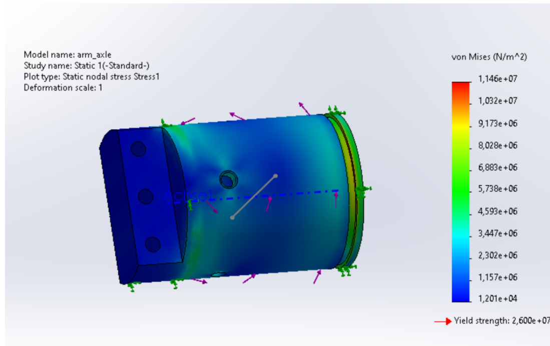


Figure 17: Force simulation performed against the 3D arm axle.

The prototyping process was mostly smooth, with some minor dimension and tolerance adjusting between iterations. In each step of this process, the design was proven to be successful, allowing the team to make steady progress without major interruptions.

In the last stage of the prototyping process, the stopper ball was inserted, and the spring was assembled together with the radial stopper bolt, which was held in place with a screw that constrained the movement to the slot in the outer part of the assembly. Finally, the stump interface and the wrist were connected to their respective places in the stump interface connector. This last part was a little bit tricky and involved some patients.

Figure 18: Prototyping Results of the new stump interface connector design

5 Result

Finally, we want to present our assembled prototype. With a lot of design interactions and the help of rapid prototyping, it was possible to build a working prototype, which an anthropomorphic look and 3 DOFs. We could show that even with limited installation space, it is possible to build an underactuated tendon driven prosthesis with five individual fingers and two grasping positions. The main goal was to stay as close to the human hand and wrist as possible. Not only this dimensions but also in terms of weight. In total, our fully assembled prototype weight 0.9 kg, which is comparable to a biological hand and forearm [1]. If we compare the weight to the previous Cybathlon prosthesis, we could reduce the weight from 1.5 kg to 0.9 kg. Imported to note is that 420g, so nearly 50%, of the weight resulting from the bigger motor units used in the wrist design. By replacing them with the smaller motor unites mentioned in Section 4.4 we could save some additional weight.

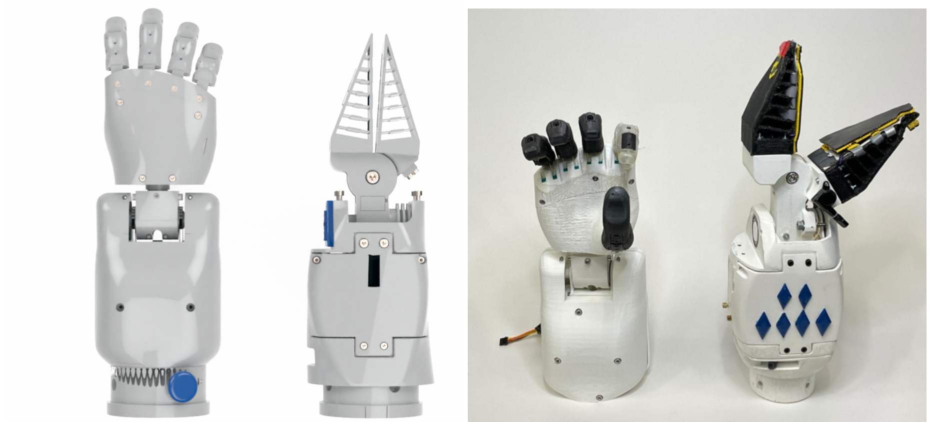


Figure 19: Comparison of our prosthesis prototype to the last build prosthesis. On the left we can see a comparison in CAD, whereas on the right the actual prototypes are depicted next to each other.While both models used the same motor units, both approaches are radically different from each other. After our wrist redesign and the integration of the bigger motors, the size of both wrist actuation units now have a similar footprint. Compared to a human hand, both wrist units are actually slightly too long resulting in a less comfortable feeling for the patient. We tried to prevent this in our initial design, however with the bigger motor units there was no other choice than increasing the wrist dimensions. This is a great example of how the choice of the motor unite dictates the resulting design.

To validate the finger actuation and the wrist movement, we tested each mechanism together with the PCB group. The finger is actuated by the Faulhaber Brushless (Series 2214 BXT R) and runs independent of the wrist movement, which allowed for parallel testing of the hand and further development at the wrist. In the following sections, we describe the test scenarios and explained initial findings.

As it is very hard to visualize this in picture, we urge you to look at the videos and the presentation slide to get a better insight at the current state.

5.1 First Finger Validation

Our first validation step took place after the tendon routing was pretensioned and all tendons were placed on their corresponding pulley. The Brushless DC motor unit is an out runner system, therefore the rotor could be easily actuated manually. This was beneficial as not electricity was needed to check grasping modes and holding forces.

In the manual test, we first tried to grasp a round, soft ball, which turned out to be very easy to hold. It was also possible to see that each finger position adapts, depending on the shape of the object. This was also the point where we discovered that the thicker tendon induces more friction into the system. This was very clear as the finger were not able to open fully by themselves. This issue could be solved by using a tendon with half the diameter of 0.26 mm.

In the second manual test we tried to grasp a coffee mug, shown in Figure 20 to see if the power grasp works also well with more ridged objects. Interesting to note is that the pinky finger yields as a resting place for the mug, so that it does not slip out. This is a grasping type that is not clearly defined but according to our observation is regularly used in the day-to-day life. The hand close as seen in Figure 20 because it is an underactuated tendon system. If the pinky finger does not encounter an obstacle, it closes until it hits the end stop.

As the pinky finger now encounters more lateral force, we attached the crucial ligaments to it to see if it stabilizes the finger elements. The mounting of the ligaments is very challenging, but just by manual inspection we noticed a huge different.

Figure 20: First validation test. Grasping a solid body, here a mug.

After those manual tests, we connected the motors, together with the PCB group. Here we tried to see if the motor was strong enough to completely close the hand. Opening the hand by a linear spring also means that increasingly more power is needed when closing the hand. In our test, the motor unit was easily capable of closing the hand while also providing additional power to apply holding force.

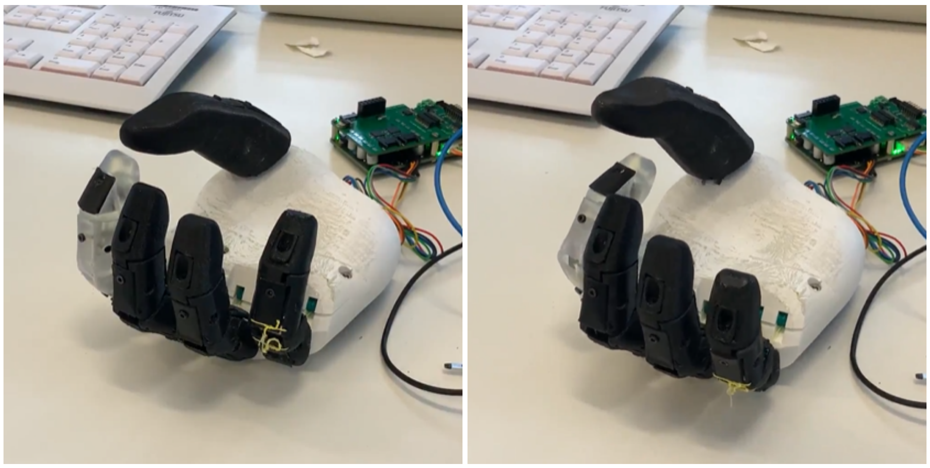


Figure 21: We achieved two different grasping type with only one DOF. On the left we can see the pinch grasping position, where the thumb directly meets the index fingers. On the right we can see the power grasping position. Here the thumb gets delayed so that all other fingers can close before and no contact between indexfinger and thumb is made. This makes it possible to grasp objects like a hammer, rackets or other tools

5.2 Wrist actuation

After tensioning the belts and initializing the motor units, the wrist was ready to be tested. From a mechanical standpoint, the mechanism was stiff and allowed for very accurate movements. In the differential drive, no teeth skipping occurred, and there was also very little play in the joints. This was vital, as any play in the wrist joint intensifies with a larger lever arm along the hand. As the motor controller might not behave like intended, it was imported to put some safety measures in place so that the system is not damaged. As flexion and extension of the wrist have an end stop at [90,-90] it must be ensured that the motor try not to move further than that. As it was not possible to do this programmatically, we had to slightly loosen the belts so that the first failure will be belt skipping some teeth.

Other than that, the wrist actuation worked very good and seems to be a very effective way of combining flexion/extension and pronation/supination.

5.3 Stump interface connector

The stump interface connector validation process involved building the part and attaching the wrist assembly and the stump interface to both ends. After that, some qualitative tests were performed. These tests consisted of unlocking the mechanism and rotating the wrist, as well as locking the mechanism and verifying that it maintains correctly the orientation of the rest of the prosthesis. These two verifications were made under several scenarios and trying to mimic the motions that a real pilot would need to operate it.

The results showed that the mechanism and the whole assembly feels stable and seems to hold well in place with the stump interface connector. While unlocked, the wrist orientation is correctly constrained to 14 possible positions and the switching between one and other requires little force and feels smooth. While the mechanism is locked, as it has already been said, the whole assembly feels sturdy and stable and presented little wobble that was in an acceptable range and didn't interfere with the main function. This last aspect was verified by heavily shaking the prosthesis while holding it from the stump interface.

But not everything was as good as that: the process of locking the mechanism with the left hand turning the knob counter-clockwise was found to be a little bit uncomfortable to do. This is an opportunity for future refinement, where a possible solution could be to invert the rotation of the knob by switching the side of the slot in the outer part of the stump interface connector.

In conclusion for this section, the stump interface connector showed to fulfill its purpose successfully. In the future, some further testing with real objects being held should be carried on to fully verify that the design and material hold up to the task. Finally, some improvement opportunities are present in the locking mechanism.

5.4 Limitations / Complications

For full disclosure, it is also important to address general limitations and complication of this prosthetic hand design. Even after decades of research, there are good reason why robotic hands are still lacking enormous functionalities compared to the complex, versatile human hand. With over 20 biomechanical degrees of freedom [4] the hand is one of the most densely innervated regions of the human body. As we only integrated 3 DOFs the hand consequently lacks functionality in one or the other area.
One influential design decision was an underactuated system. Underactuated fingers generally refers to a system where the controller has no full control over each finger angle or position. The fingers close until they hit an obstacle. Consequently, it is possible to implement adaptable grasps, without implementing complex feedback controllers. When no sensory input is available, it is still possible to grasp an object with equal holding force on each finger, which is vital

when grasping heavy objects.
On the other hand, it also has implications on the assembly process as well as potential control systems. Unlike fully-actuated systems, the control designer has no choice but to reason about the more complex dynamics of the plant in the control design. Group 3 tried to model our tendon driven actuation using Simulink. It turned out to by highly non-linear. If one tried to implement a feedback controller, it would dramatically complicate the process and even might not be feasible. For further information, see Group's 3 report.
In our design, a continuous tendon was used to actuate every finger in series. This meant that the assembly process was one of the bottlenecks in the production of the hand. It took nearly two full days to route it though each finger and connect each end to the correct pulley of the motor unit. Such long assembly times also limited us from improving the design, as even small changes always resulted in a tedious reassembling process.

Another drawback that was introduced to as a compromise to save space, is the asymmetric design of the wrist. It might lead to more uncomfortable handling of the prosthesis, as the center of mass is non-collinear with the rotational axis. However, in our design, no major abnormalities during handling of the prosthesis have been noticed. Other than that, we did not further investigate this drawback. It might be relevant, but was negligible in our case.

6 Outlook

During the course of the hand prototyping, our goal always was to present a functioning hand prototype with the concepts introduced in the previous semester. We wanted to show that it is possible to build a prototype in a timeframe of two semesters. We gained a lot of understanding what the main difficulties are when designing especially anthropomorphic hands.

As time was limited in the semester, we had lots of ideas to further improve our design in all kinds of areas. Therefore, we comprised a list of fixes that can be made to improve the current design and deal with the issues that we described in this report. You can see an excerpt in Figure 22 and find the entire file in our folder
[file: "./Additional Material/Prosthesis_Improvement_Cybathlon.xlsx"]

2	Part	Issue	Improvement
3	***Palm***		
4	stopping surface for fingers (ribs in between fingers)	finger collides with ribs → flexion of fingers no fully possible	reduce size of ribs, increase width of stopping surface
5	Springsteel mounting point	pretentioning is not implemented	add angle to increase tenstion in normal finger position
6		side walls are too far apart (finger mounting)	adjust width to 10 mm including tolerances
7	mounting plate fingers	does not meet with the finger element. Aesthetically not appealing.	increase mounting plate overlap. Or adjust mounting point (move closer to motor)
8	tendon routing, horizontal alignment to the fingers	2 mm pins do not fit into hole. 3d printed part has different tolerances for inner diameter	change hole size to 2,5 mm. Look at the hole for a M3 thought hole.

Figure 22: An excerpt of the current design issues and improvements.

7 Conclusion

The prosthesis was specifically designed for competing in the Cybathlon Challenge, and its function is tuned for optimal performance in the tasks presented there. These tasks mirror challenges that an amputee will experience in everyday life.

We could underpin that our previously developed hand prototype is lightweight, anthropomorphic and agility with a functioning 2 DOF differential wrist drive as well a 1 DOF finger actuation mechanism. The serial unteractuaded tendon routing idea worked as intended, and a clear difference between the two grasping modes is visible. The bidirectional activation of the tendon is an interesting concept, and enables an additional feature with only 1 DOF.

Furthermore, the leaf spring finger design was improved to have a more human like look as well as more streamlined assembly process. Cruciate ligaments are a very effective way to add additional torsional strength while maintaining the full range of movement.

After nearly one year of work and effort, we are proud to have build a functional, innovative, and new type of prosthesis, which might inspire other research groups to adapt certain mechanisms.

References

[1] Human Body Part Weights. `https://robslink.com/SAS/democd79/body_part_weights.htm`.

[2] Leon Kiesgen, Johannes Frey, and Christopher Herneth. Cybathlon - CAD1 - Report, July 2021.

[3] Stefan Salminger, Heiko Stino, Lukas H. Pichler, Clemens Gstoettner, Agnes Sturma, Johannes A. Mayer, Michael Szivak, and Oskar C. Aszmann. Current rates of prosthetic usage in upper-limb amputees – have innovations had an impact on device acceptance? *Disability and Rehabilitation*, 0(0):1–12, 2020. PMID: 33377803.

[4] Yuke Yan, James M. Goodman, Dalton D. Moore, Sara A. Solla, and Sliman J. Bensmaia. Unexpected complexity of everyday manual behaviors. *Nature Communications*, 11(1):3564, July 2020.