ARM3D

A 3D printed transhumeral arm prosthesis

Madelon MA Kusters

TU Delft
Biomedical Engineering
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Student no.: 4752252
Supervisor: Dr. ir. D.H. Plettenburg
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Abstract

Aim: This project aims to design a lightweight, inexpensive and easy to use upper arm prosthesis through improving the design of ARM3D, which is a 3D printed body-powered transhumeral arm prosthesis. This study will cover general shortcomings of body-powered arm prostheses as the weight, cost, amount of parts and limited accessibility of them. This study also focusses on a natural appearance of the prosthetic arm.

Results: The improved design of ARM3D is made of six 3D printed and eight non-3D printed parts. It has three Degrees of Freedom (DOF's), one control cable, a harness both to suspend and control the prosthesis, an active voluntary closing hand, a passive rotating wrist joint and a passive elbow hinge joint. The prosthesis costs €59,68 and weighs 403 g. It takes 3 days, 6 hours and 47 minutes to print and 15 minutes to assemble. The maximum open hand width is 64 mm and the prosthesis needs 15 N of tension force on the control cable to operate. Furthermore, it is possible to paint the prosthetic fingernails and to remove the nail polish.

Conclusion: An improved design of the ARM3D prosthesis is presented in this paper. ARM3D is almost entirely 3D printed. It is a lightweight and inexpensive device. A field study is required to gather more information whether the prosthesis is easy to use.

Keywords

3D printed; transhumeral; upper arm; prosthesis; 3D printing; body-powered; lightweight

Background and aim

Years before the existence of 3D printing technique, there were prostheses available for upper arm amputees, among which body-powered prostheses. Generally, the latter is controlled by one or two control cables, combined with a harness. Unfortunately, these traditional body-powered prostheses do have shortcomings. Most importantly, they are too heavy. The weight of the device is an essential reason for upper limb prostheses rejection.[1] Furthermore, they are expensive, contain many parts and have limited accessibility.

The last decade, significant development has occurred in 3D printing of upper limb prostheses,[2] because 3D printing technique has the potential to provide a solution to most of the disadvantages of traditional body-powered upper limb prostheses. The material, Polylactic Acid (PLA), is light, affordable and accessible.[3] Therefore, it is also beneficial for children, the lower class of the society and developing countries.

There are 3D printed transradial as well as 3D printed hand prostheses available. However, there are very few 3D printed transhumeral arm prostheses available currently. During the author's literature study, only one such prosthesis was found that was both tested by an amputee and proved functional.[4]

In a preliminary study, I designed a body-powered, 3D printed, transhumeral arm prosthesis called ARM3D.[5] It weighed 775,4 g, cost €51,18 and consisted of eighteen 3D printed parts. A test by one amputee showed that the subject was able to do daily bi-lateral tasks as opening a bottle and cutting vegetables. However, the test also showed shortcomings, such as a short lifespan of some of ARM3D's parts.

Therefore, the goal of this project is to improve the design of ARM3D. Most importantly, by strengthening its joints and extending its lifespan. Furthermore, by reducing its weight, amount of (3D printed) parts, assembly time and cost. This study also focusses on a natural appearance of the prosthetic arm.

This master thesis project aims to design a lightweight, inexpensive and easy to use transhumeral arm prosthesis through improving the design of ARM3D and thereby fill in the gap in the current market supply of 3D printed transhumeral arm prostheses.

Method

The major shortcoming of the old design of ARM3D was the short lifespan of its joints. Before starting to improve these, a literature study was done to investigate what has already been done in 3D printed wrist and elbow joints in transradial and transhumeral arm prostheses. This research showed that a rotating wrist joint with 1 DOF (pronation and supination) was the most commonly used 3D printed wrist joint and that there is a lack of 3D printed elbow joints. Furthermore, a field study during the author's internship abroad gained an understanding in the experiences of transradial and transhumeral amputees with 3D printed arm prostheses and the advantages and disadvantages of them. The most recurring issue was the unnatural appearance of the printed device.

This project made use of an iterative design process [6] for two reasons. Firstly, it is an effective way to design a functional device in a limited timeframe since it is possible to detect problems earlier on in the design process.[6] Secondly, there is not much known about 3D printed transhumeral prostheses in literature. After finding a supposed solution to an individual component, its working principle was printed and tested before integrating it into the prosthesis' design. Figure 1 shows these iterative design methodology steps.

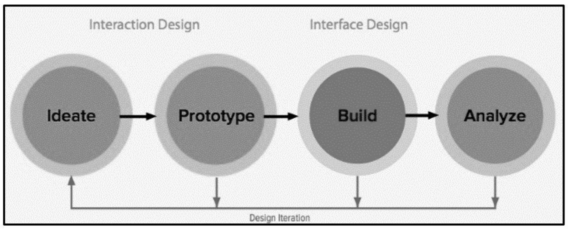

Figure 1: Iterative design methodology steps.[6]

Requirements

Usually, body-powered transhumeral arm prostheses have two DOF's: flexion/extension of the lower arm and opening/closing of the hand.[7] Sometimes they contain a third DOF: rotation in the wrist joint.[7] Tests with an upper arm amputee in a preliminary study showed the significance of this third DOF. Therefore, it is included in the requirements of ARM3D.

The improved design of ARM3D needed to have:

- Three DOF's: opening/closing of the hand, pro-/supination of the hand and flexion/extension of the lower arm
- A minimal amount of parts
- The ambition to be entirely 3D printed
- Body-powered control by one control cable
- A harness both to suspend and control the prosthesis
- An active, voluntary closing hand
- A passive rotating wrist joint that can be locked in position
- A passive flexion/extension elbow joint that can be locked in position

Apart from these technical requirements, a natural appearance of the prosthetic arm was kept in mind with all design considerations. The final design needed to have the dimensions and shape like a human arm as much as possible.

Results

The improved design of ARM3D is shown in figure 2. This 3D printed transhumeral arm prosthesis has three DOF's. It consists of six 3D printed and eight non-3D printed parts. The prosthesis is body-powered controlled by one control cable that consists of two parts: the lower arm part (Figure 2h) and the upper arm part (Figure 2i). The control cable runs internally through the prosthesis. A harness is used both to suspend and control the prosthesis. The hand is an active, voluntary closing system controlled by the control cable. Rotation of the wrist and flexion/extension of the elbow joint are passive systems controlled by the non-amputated hand. The prosthesis costs €59,68 and weighs 403 g. It takes 3 days, 6 hours and 47 minutes to print and 15 minutes to assemble. Refer to Table 1 and 2 for more detailed information.

Mechanical design

This section will elaborate on the prosthesis' mechanical design. The six 3D printed parts will be discussed first followed by the non-3D printed parts. Lastly, the harness to which the prosthesis is connected will be talked upon.

Hand (including wrist joint)

Two significant improvements were made to the hand design (Figure 2a). The new design is made of a single part and the wrist joint is strengthened by a 3D printed screw thread.

In order to design the hand as a single part, the control mechanism of the voluntary closing hand was simplified. It was done by replacing the thumb joint by a fixed thumb in an open hand position and by connecting the four fingers to the same bar to have it function as one joint (Figure 3a). On the palmar side, the lower arm part of the control cable is connected between the middle- and ring finger to close the hand through tension force on this cable (Figure 3b). On the dorsal side, a tension spring is placed just below the knuckles and between the middle- and ring finger to extend the fingers after tension on the control cable is released (Figure 3c).

It is possible to print the fingers joint at once because of the use of two print materials: PLA and Polyvinyl Alcohol (PVA). PVA is soluble in water and used as support material. In the design, there is a gap of 2mm around the joint. Therefore, this gap will be filled with PVA while printing and will be opened up after the part has been soaking in water for two days.

An additional benefit to the new hand design is that this control mechanism is less susceptible to wear and tear. Furthermore, the maximum opening width between thumb and index finger, 64 mm, is unaffected.

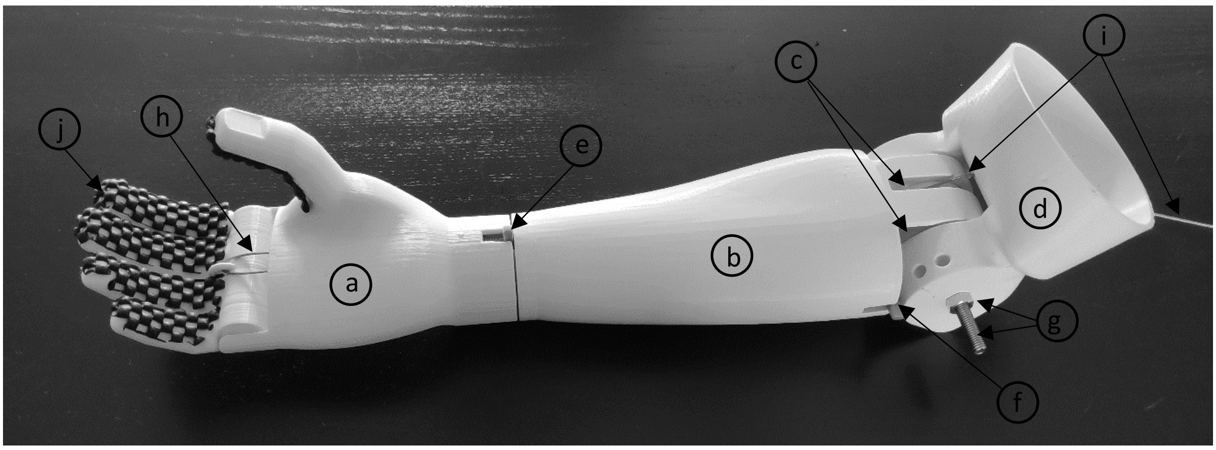

Figure 2: ARM3D; body-powered 3D printed upper arm prosthesis, which consists of six 3D printed parts. a) Hand. b) Lower arm. c) Elbow pulley. d) Upper arm. e) Wrist joint pint. f) Elbow joint pin. g) Bolt and nut. h) Lower arm part of the control cable. i) Upper arm part of the control cable. j) Anti-slip material.

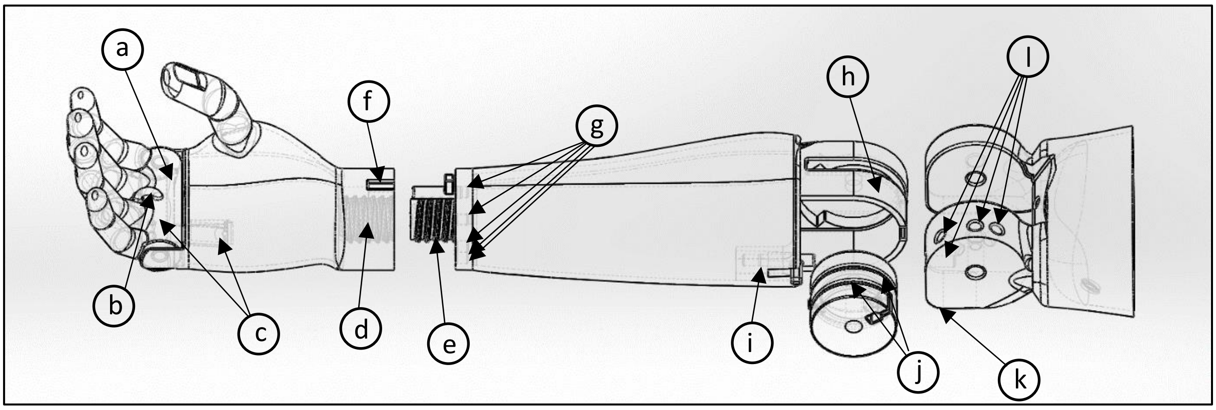

Figure 3: ARM3D, SolidWorks exploded view. a) Bar to which all fingers are connected. b) Place were the lower arm part of the control cable is connected. c) Place were the tension spring is connected. d) Internal screw thread for the wrist joint. e) External screw thread for the wrist joint. f) Spring-loaded lever mechanism for the wrist joint. g) Five holes that define the possible wrist joint positions. h) Elbow pulley cover. i) Spring-loaded lever mechanism for the elbow joint. j) Place where the two parts of the control cable are connected to the elbow pulley. k) Shape that prevents elbow joint from overstretching. l) Four holes that define the possible elbow joint positions.

A screw thread is added inside the wrist joint to strengthen it as well as to remove the small tolerance in the joint which allowed sideways movements as (about 10°) ulnar- and radial abduction. The internal thread is placed at the proximal part of the hand (Figure 3d), while the external thread is situated at the distal end of the lower arm (Figure 3e). The hand can pro- and supinate over the lower arm through the screw thread. A spring-loaded lever mechanism (Figure 3f) is used to lock the wrist joint in the desired position. Five holes on the distal end of the lower arm define these positions, namely 0° (anatomical position), 45°, 90°, 135° and 180° pronation (Figure 3g).

Refer to appendix 2 for detailed pictures, drawings and dimensions of the hand and wrist joint design.

Lower arm

The lower arm is also made of a single 3D printed part (Figure 2b). It serves as a connection part between the hand and upper arm and also contains the elbow pulley, which will be discussed later.

To connect the lower- to the upper arm like a hinge joint (the elbow joint), a hole runs from the medial to the lateral side through the elbow pulley cover (Figure 3h) which is positioned at the proximal end of the lower arm. A spring-loaded lever mechanism, placed on the proximal, medial side of the lower arm, is used here as well to lock the elbow joint in the desired position (Figure 3i). Furthermore, a hole of 5 mm diameter is running through the inside of the external screw thread (on the distal part of the lower arm) to connect the lower arm part of the control cable to the fingers joint.

Refer to appendix 3 for detailed pictures, drawings and dimensions of the lower arm design.

Elbow pulley

Traditionally, control cables of transhumeral body-powered prostheses run externally on the lateral side of the elbow joint.[8] However, appearance, as well as ease of wearing the prosthesis under clothes, improves when the control cable runs internally through the device. A pulley inside the elbow joint (Figure 2c) is used to apply this to the ARM3D design.

The two parts of the control cable are connected to the pulley (Figure 3j). The lower arm part of the control cable runs from the fingers to the pulley. The upper arm part runs from the pulley to the harness. Pulling the upper arm part generates a clockwise movement of the pulley, causing tension on the lower arm part, and thereby flexes the fingers. The earlier mentioned tension spring on the dorsal side of the hand then puts the pulley and fingers in the original position after tension on the upper arm part of the control cable is released. When the pully reaches its maximum rotation of 90°, tension on the upper arm part of the control cable will generate flexion movement of the lower arm.

Refer to appendix 4 for detailed pictures, drawings and dimensions of the elbow pulley design.

Upper arm

The upper arm of the prosthesis is made of a single part and has two functions (Figure 2d). It completes the elbow joint and connects the prosthesis to the harness and the user's stump. Besides that, the upper arm part of the prosthesis determines the appearance of the elbow because the upper arm fits over the lower arm part around the elbow joint. Next to a most natural look, the upper arm has a functional shape around the elbow to prevent the elbow joint from overstretching (Figure 3k). Moreover, there are four holes designed on the medial part of the upper arm (Figure 3l). These define the possible lower arm positions the elbow joint can be locked in (fully stretched (0°), 45°, 90° or 116° flexion). The proximal part of the upper arm, which is bowl-shaped, will be custom made to fit perfectly around the subject's stump.

Refer to appendix 5 for detailed pictures, drawings and dimensions of the upper arm design.

Wrist joint pin

A small pin is designed to function, together with a compression spring, as a spring-loaded lever mechanism (Figure 3f). The spring pushes the pin into one of the five wrist joint holes (Figure 3g) what locks the wrist joint. Passively, by the subject's non-amputated hand, this pin can be pushed distally which loads the spring. While holding tension on the spring, the wrist joint can rotate. After releasing the pin, the spring pushes the pin back in a hole which locks the joint in the desired pro-/supination position (Figure 2e).

Refer to appendix 6 for detailed pictures, drawings and dimensions of the wrist joint pin.

Elbow joint pin

The elbow joint pin design and its working principle are similar to that of the wrist joint's pin. Together with a compression spring, it functions as a spring-loaded lever mechanism to lock the elbow joint in the desired flexion/extension position of the lower arm (Figure 2f, 3i, 3l).

Refer to appendix 7 for detailed pictures, drawings and dimensions of the elbow joint pin.

Non-3D printed parts

The following eight non-3D printed parts are necessary to build the ARM3D prosthesis.

A tension spring (free length: 30,4 mm, outside diameter: 6 mm, rate N/mm: 0,12)[9] is used at the dorsal side of the hand (Appendix 1, Picture 1). This spring pulls the fingers back in an opened hand position after tension on the upper arm part of the control cable is released.

Two compression springs (free length: 12,7 mm, outside diameter: 6 mm, number of coils: 5¾, rate of stiffness: 1,44 N/mm)[10] are used in the wrist- and elbow joint's spring-loaded lever mechanisms (Appendix 1, Picture 6).

A metal hinge axis, fabricated by a bolt and nut (coach bolt and nut M6x100 mm)[11],[12], is used for the elbow hinge joint of the prosthesis (Figure 2g). The bolt goes through the upper arm, lower arm and elbow pulley.

Two inner bike brake cables (1,5 mm diameter)[13] are used for the two parts of the control cable (Figure 2h,i).

Anti-slip material is glued to the palmar side of the prosthesis' hand to create friction between the hand and objects (Figure 2j).[14] It reduces the required tension force and pinch force to hold objects.

Harness

Figure 4 shows the improved design of the harness which suspends and controls the

Table 1: Specifications of all 3D printed parts.[17-19]
**Including support material*

	Weight [g]	PLA [g]	PVA [g]	Print time [d:h:min]	Material costs* [€]
Hand	110	110	72	1:2:42	15,79
Lower arm	116	114	98	1:5:42	19,62
Elbow pulley	21	24	5	0:2:46	1,97
Upper arm	118	92	42	0:15:57	10,90
Wrist joint pin	0,3	<1	<1	0:0:10	0,19
Elbow joint pin	0,4	<1	<1	0:0:15	0,18
Buckles (3x)	22	22	3	0:3:15	1,58

Table 2: Specifications of all non 3D printed parts.[11-14],[20],[21]

	Weight [g]	Cost [€]
Tension spring	0,4	0,82
Compression spring (2x)	0,4	0,53
Bolt	21	0,13
Nut	1	0,02
Control cable (2x)	14	7,78
Anti-slip	0,5	1,75
Webbing	31	2,88

prosthesis. Its material is black webbing.[15] Its design is based on the figure 9 harness.[16] Only, this harness has three ends instead of one on the amputated arm side (Figure 4a,b,c). Each end is connected respectively to the ventral, lateral and dorsal side of the upper arm part of ARM3D by three 3D printed buckles (Figure 4d). Through these buckles also, the length of the harness is adjustable. The upper arm part of the control cable is connected to the harness at the middle of the subjects back (Figure 4e). The loop of the harness is placed around the shoulder of the non-amputated arm. Tension on the control cable, and therefore movement of the prosthesis, is generated by flexion or medial rotation of this shoulder.

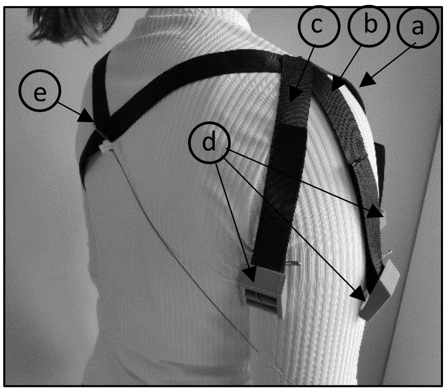

Figure 4: Harness which suspends and controls ARM3D.

Refer to appendix 8 for detailed pictures of the harness design.

Anti-slip sock

An extra part was added to ARM3D after a problem came to light in the old design. When the subject's stump is fully round, instead of a bit oval, the prosthesis was able to rotate around the stump. An anti-slip sock (made of elastic band and anti-slip material)[14],[22] is manufactured to prevent this (Figure 5). The double-sided anti-slip sock will not slide over the skin nor prosthesis and therefore hold the device in place.

Figure 5: Anti-slip sock to prevent rotation of the prosthesis around the stump.

Specifications

Table 1 shows the weight, print time, costs and amount of PLA and support material (PVA) of all 3D printed parts of ARM3D and the harness. Table 2 shows the weight and expenses of the non-3D printed parts of the prosthesis and harness.

3D printing specifications

An Ultimaker 3 Extended [23], which is able to print two materials at the same time, is used as the 3D printer in this study. Its build volume is 215x215x300 mm. Material 1, PLA white, was printed with the following printer settings: print core AA 0.4, layer height 0.2mm, infill density 40%, infill pattern triangles, print speed 70 mm/s, printing temperature 210 °C and build plate temperature 60 °C. Material 2, PVA natural, was used as support material and was printed with the following printer settings: print core BB 0.4, layer height 0.2mm, infill density 20%, infill pattern triangles, print speed 35 mm/s, printing temperature 215 °C and build plate temperature 60 °C. Support placement was everywhere and a brim was also printed by support material.

Tests

Traction force tests on the control cable were done to examine whether ARM3D is easy to use. Another test was executed to gather information about the amount of traction force with the corresponding pinch force. In addition, the maximum pinch force was measured. These tests were executed using Unster, Standalone and weight plates.[24-26] The results are shown in Table 3. Additionally, it was tested if ARM3D was able to carry a bag of 1 kg in various elbow flexion and wrist joint lock positions. Pictures of this test are shown in appendix 9.

It came to light, during the author's internships abroad, that a natural appearance of prostheses is desired. Most noticeable are the fingernails. Therefore, regarding the natural appearance of ARM3D, a test was done to investigate whether it was possible to paint the prosthetic nails and the possibilities to remove nail polish. This turned out to be possible with regular nail polish [27] and nail polish remover with acetone.[28] Remover without acetone damages the PLA.

Furthermore, the control cable displacements required to control the prosthesis were measured through two tasks: closing the hand in various lock positions of the elbow joint and flexing the elbow to different angles. Different lock positions of the wrist joint did not influence the cable displacement (<1 mm). Table 4 shows the results of this test.

Table 3: Results of traction force tests.

<table>
<tr><th colspan="2">Task</th><th>Tensile force [kg]</th><th>Tensile force [N]</th></tr>
<tr><td rowspan="4">Close hand with elbow flexion locked at</td><td>0°</td><td>1,5</td><td>14,7</td></tr>
<tr><td>45°</td><td>1,4</td><td>13,7</td></tr>
<tr><td>90°</td><td>1,6</td><td>15,7</td></tr>
<tr><td>116°</td><td>1,4</td><td>13,7</td></tr>
<tr><td rowspan="3">Flex elbow to</td><td>45°</td><td>2,8</td><td>27,5</td></tr>
<tr><td>90°</td><td>3,5</td><td>34,3</td></tr>
<tr><td>116°</td><td>4,3</td><td>42,2</td></tr>
<tr><td colspan="2">Holding an empty bottle of beer (30cl)</td><td>1,2</td><td>11,8</td></tr>
<tr><td colspan="2">Holding a full bottle of beer (30cl)</td><td>2,2</td><td>21,6</td></tr>
<tr><td rowspan="3">Pinch force by tension force of</td><td>1,5 kg</td><td>1</td><td>9,8</td></tr>
<tr><td>2,5 kg</td><td>1</td><td>9,8</td></tr>
<tr><td>3,5 kg</td><td>1,2</td><td>11,8</td></tr>
<tr><td colspan="2">Maximum pinch force</td><td>1,2</td><td>11,8</td></tr>
</table>

Table 4: Required control cable displacements to close the hand or flex the elbow.

<table>
<tr><th colspan="2">Task</th><th>Cable displacement [mm]</th></tr>
<tr><td rowspan="4">Close hand with elbow flexion of</td><td>0°</td><td>13</td></tr>
<tr><td>45°</td><td>23</td></tr>
<tr><td>90°</td><td>37</td></tr>
<tr><td>116°</td><td>45</td></tr>
<tr><td rowspan="3">Flex elbow to</td><td>45°</td><td>27</td></tr>
<tr><td>90°</td><td>38</td></tr>
<tr><td>116°</td><td>45</td></tr>
</table>

A final test was executed to measure ARM3D's assembly time. To begin with, all 3D printed parts had to be soaked in water for two days in order to remove the support material. After this, it took five minutes to glue the anti-slip material on the palmar side of the hand and another ten minutes to assemble all twelve parts (Appendix 1, Picture 6).

SolidWorks vonMises stress simulations

In SolidWorks vonMises stress simulations on the prosthesis' individual parts are done to detect the design's weak spots. These are shown in appendix 10. A trade-off will have to be made between weight and strength of the prosthesis. Therefore, a field study is necessary to investigate what loads and traction forces are required for the use of the prosthesis. In this manner, it can be determined to what extent these spots are too weak and do need extra support.

Discussion

This study aimed to design a lightweight, inexpensive and easy to use transhumeral arm prosthesis through improving the design of ARM3D.

Lightweight

With regards to the weight of the prosthesis, the improved design of ARM3D reached its goal. The prosthesis weighs 403 g excluding the harness. This is half the weight of a 3D printed shoulder prosthesis (890 g).[4] The weight of ARM3D's hand is 110 g. In comparison to thirteen other hand prostheses, weighing in the range of 112-1315 g, it is the lightest one out of them all.[2],[4],[29],[30]

Inexpensive

ARM3D's 3D print material costs are €48,65. Its costs including all non-3D print materials are €59,68. Unfortunately, it cannot be compared to other 3D printed transhumeral arm prostheses costs because these were not found during literature study. However, the cost of a 3D printed shoulder prosthesis is around €168.[4] Considering the extra shoulder part, this is still twice as expensive as ARM3D. In addition, the cost of ARM3D's hand only is €18,36 (including non-3D printed parts). The material costs of 21 found 3D printed hands range between €4,20-€420,-.[2],[29] Relatively speaking, ARM3D's hand is inexpensive as it is ranked in the bottom 4% of this range.

Easy to use

ARM3D is a body-powered controlled prosthesis. In general, body-powered prostheses have advantages in training time and feedback.[31] The old design of ARM3D was tested by one amputee who was able to do daily bi-lateral tasks such as opening a bottle and cutting vegetables at the first trial. A field study is essential to know if this is also the case with the new design. However, the expectation regarding training time is that it will be equal to that of the old design. Furthermore, the maximum amount of tension force required to control the hand of ARM3D is 15,7 N. 21,6 N is necessary to hold a full bottle of beer. According to Monica Hichert, transradial prosthesis users were able to generate maximum forces on the control cable ranging from 87 to 538N.[32] Nevertheless, cable forces should be kept below 38 N to be a fatigue-free operation.[32] The tension forces required to control ARM3D are below both these values. Based on the above, it can be stated that ARM3D is an easy to use prosthesis.

The goal of this project was to improve the design of ARM3D. Most importantly by strengthening its joints and extending its lifespan. Furthermore, by reducing its weight, amount of (3D printed) parts, assembly time and cost. This study also focused on a natural appearance of the prosthetic arm.

Strengthen joints and extend lifespan

ARM3D's wrist- and elbow joints are strengthened by inserting a screw thread on the inside of the wrist joint and by replacing the 3D printed elbow hinge joint axis with a metal one. These improvements are expected to affect ARM3D's lifespan positively, but further tests are required to investigate to what extent.

Improve ARM3D's old design

The improved design of ARM3D is reduced by 372,4 g (775,4 g to 403 g), twelve 3D printed (18 to 6) and nine (17 to 8) non-3D printed parts. The assembly time is reduced by 45 minutes (60 to 15 minutes). Solely the costs of the new design are not reduced but increased by €8,50 (from €51,18 to €59,68). In addition, the required tensile force to close the hand at both 0° and 90° of elbow flexion has halved.

Therefore, this study has achieved its goal of improving ARM3D's old design.

Natural appearance

To achieve a more natural look of the device, the surface of the prosthesis was smoothed. This was done by running the control cable through the inside of the prosthesis as well as by eliminating protruding parts. Moreover, a natural color of the device is essential too. Despite the fact that it is possible to print PLA in different colors, there is not a color palette available for varying skin tones.[33] The possibility of using a sleeve in the amputee's exact skin tone should be investigated to create an even more natural appearance of the prosthesis.

Requirements

The improved design of ARM3D has met all its set requirements. It has 3 DOF's, a minimized amount of parts and the ambition to be entirely 3D printed. It is body-powered controlled by one control cable split into two parts. The harness both suspends and controls the prosthesis. The prosthesis has an active, voluntary closing hand, a passive rotating wrist joint (180° pronation) and a passive elbow hinge joint (116° elbow flexion). Both passive joints can be locked in their five and four positions respectively.

Tests

Tensile- and pinch force tests were done with ARM3D. Also, the control cable displacements required to control the prosthesis were measured.

Tensile force

Required tensile forces to flex the elbow were measured. Locking the elbow joint in the desired position is passively controlled by the amputee's non-amputated hand though. Therefore, the expectation is that in practice, the amputee will not use tensile force on the control cable to execute flexion movement of the elbow.

Pinch force

The hand of ARM3D generates a pinch force of 9,8 N at a tension force on the control cable of 14,7 N. The maximum pinch force of 11,8 N is reached at a tension force of 34,3 N. The hand prosthesis of Cuellar et al., is capable of reaching reasonable pinch forces to execute various daily activities with 0-2 N pinch force at a range of 15-40 N tension force.[28] Therefore, the feasible pinch forces of the hand of ARM3D are found sufficient.

Control cable displacement

The required control cable displacements to close the hand of ARM3D, in various elbow flexion lock positions, vary between 13-45 mm. A preliminary study shows that maximum possible cable displacements are in the range of 42,7-75,2 mm.[34] Maximum possible cable displacements generated solely by protraction of the amputated side's shoulder are shown to vary between 29-46 mm.[32] Based on these two studies, ARM3D's required control cable displacements are feasible. Moreover, most control of ARM3D can be executed by protraction of the amputated side's shoulder only.

Opening width

The average human hand has an opening width of 75-90 mm.[2] The maximum opening width between the thumb and index finger of ARM3D is less with 64 mm. Further research should indicate whether this is sufficient and investigate the possibilities of increasing the opening width to the average values if it turns out to be necessary.

Control cable path

Traditionally, control cables of transhumeral body-powered prostheses run externally on the lateral side of the elbow joint.[8] Unique about this design is that the control cable runs internally through the device. In the author's opinion, this is a great advantage regarding appearance as well as ease of wearing of the device.

Rotation of the device around the stump

The anti-slip sock is manufactured to prevent rotation of the prosthesis around the stump in case the amputee's stump is fully round. Although this double sided anti-slip sock will keep the prosthesis in place, it will not eliminate the rotating moment around the stump. It probably will create an even larger moment which will result in stump irritations as blisters. A thorough study should be conducted in order to provide a solution to this problem.

Applicability

ARM3D is designed for a right armed amputee. However, it is possible to print ARM3D for both right and left armed amputees with the mirror function in Ultimaker Cura slicer.[19] This program also provides a scaling function which makes it possible to adapt the size of the prosthesis easily. In addition, the scaling function combined with the low cost of the prosthesis makes ARM3D suitable for children, because they grow fast and therefore need a new prosthesis more often than adults.

Recommendations

Despite the ability to lock the wrist joint in a range of 0°-180° pronation, it is possible to rotate the hand further over the screw thread. This would result in an unnatural movement of the wrist joint, which is undesirable. A follow-up study should consider preventing pronation over 180°.

Unfortunately, this study lacks a maximum force test to measure at what amount of force the pins of the wrist- and elbow joint lock mechanisms yield. It is recommended to conduct such a test later on. If this test proves the pins too weak, it should be considered replacing them by metal ones.

Although the surface of the back of the prosthetic hand is smooth, the tension spring used for the voluntary closing hand mechanism is visible. A suggestion to solve this issue would be to cover the spring in some way to improve the appearance of the hand more.

Conclusion

An improved design of the ARM3D prosthesis is presented in this paper. ARM3D is almost entirely 3D printed and consists of fourteen parts. It is a lightweight, inexpensive and easy to use transhumeral prosthesis. The wrist- and elbow joints are strengthened compared to the joints in the old design. The improved design of the prosthetic arm has a more natural appearance, because the control cable runs internally through the device. Further research is necessary to investigate the lifespan of ARM3D. A field study is required to gather more information regarding training time and ease of use of the device.

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Appendices

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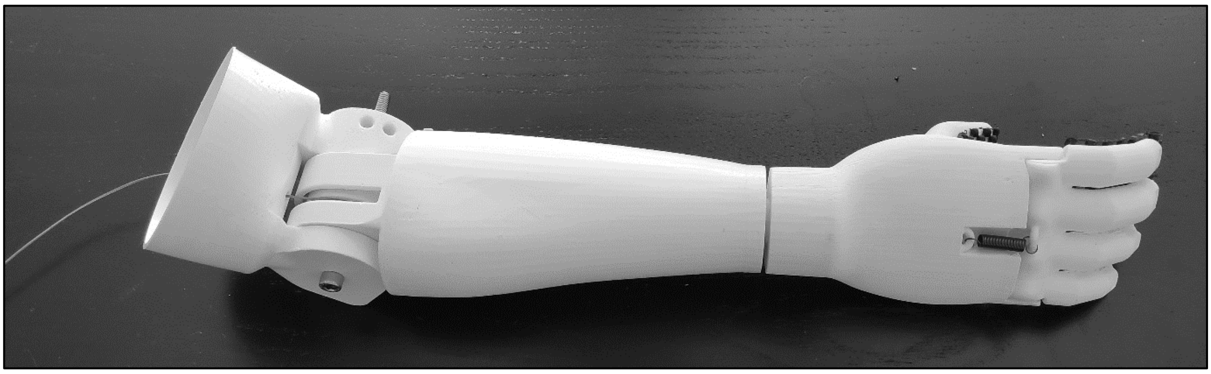
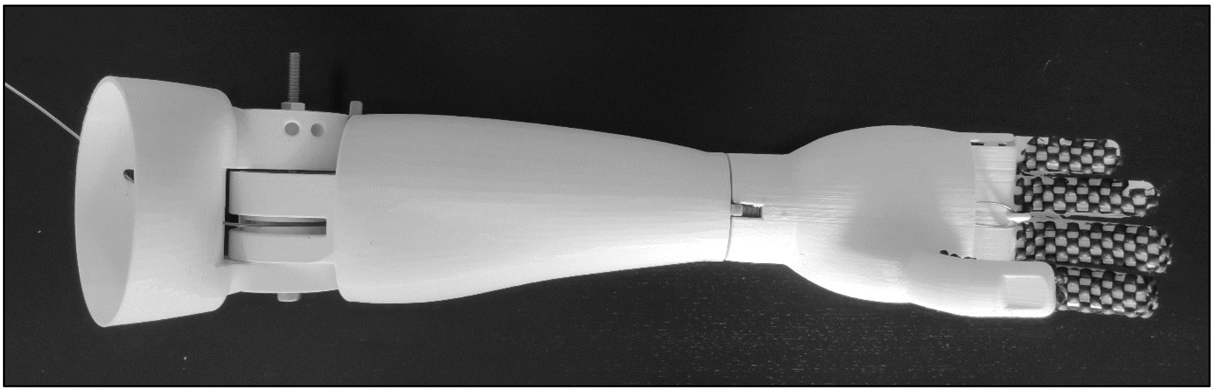
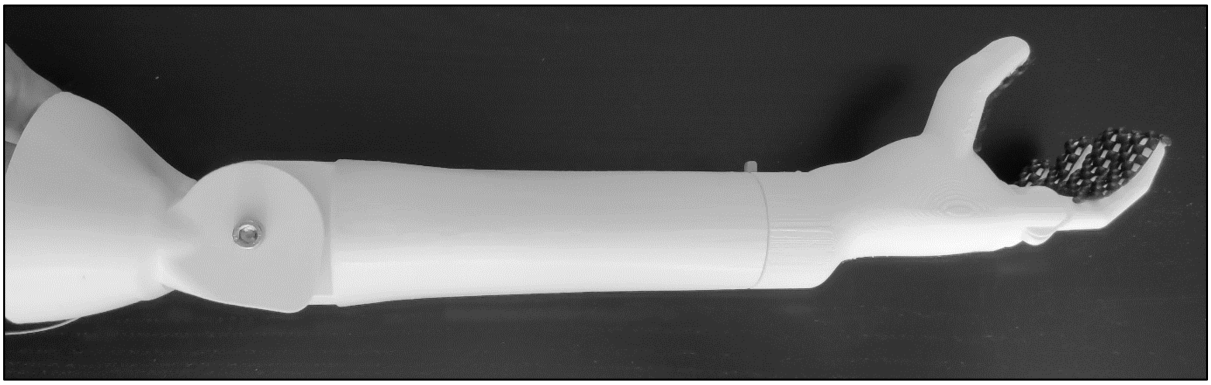
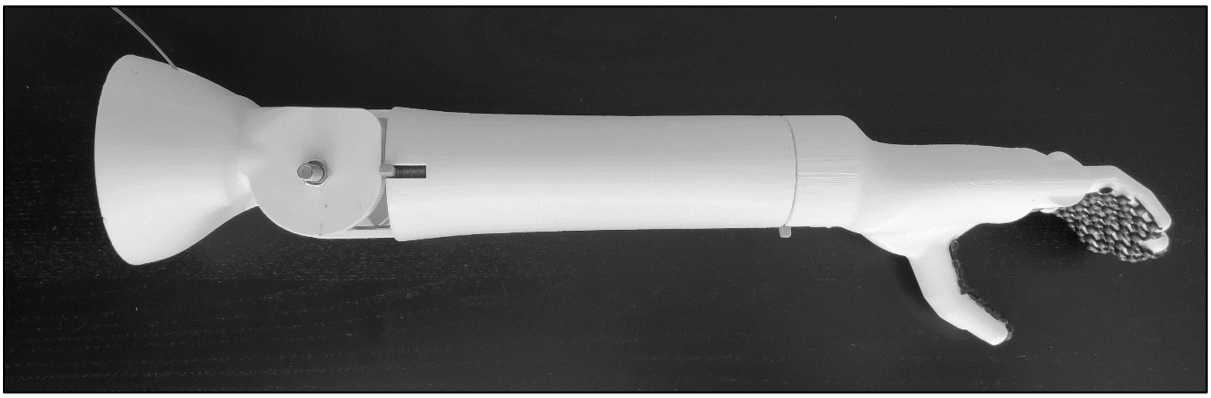
Appendix 1: ARM3D

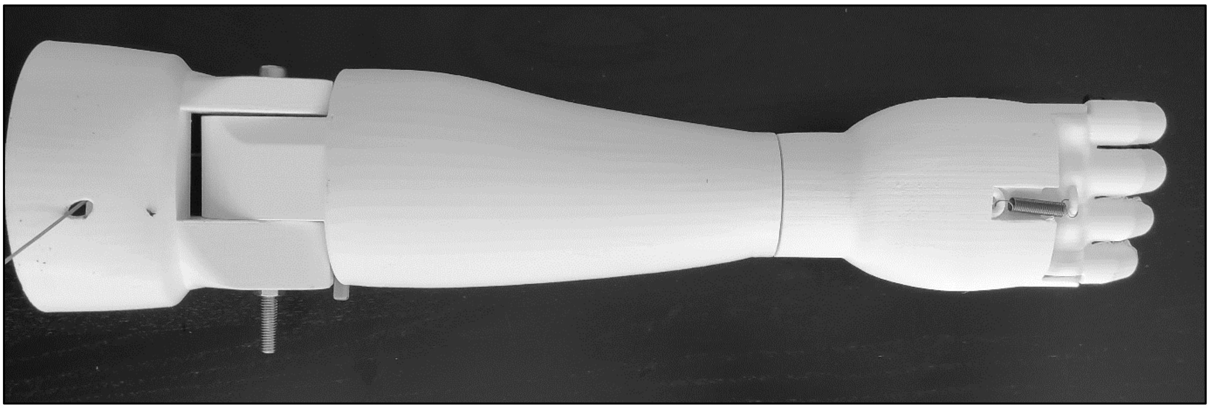
Pictures of ARM3D from different angles are shown in this appendix. A picture that gives an overview of all parts of the ARM3D prosthesis is also added to this appendix.

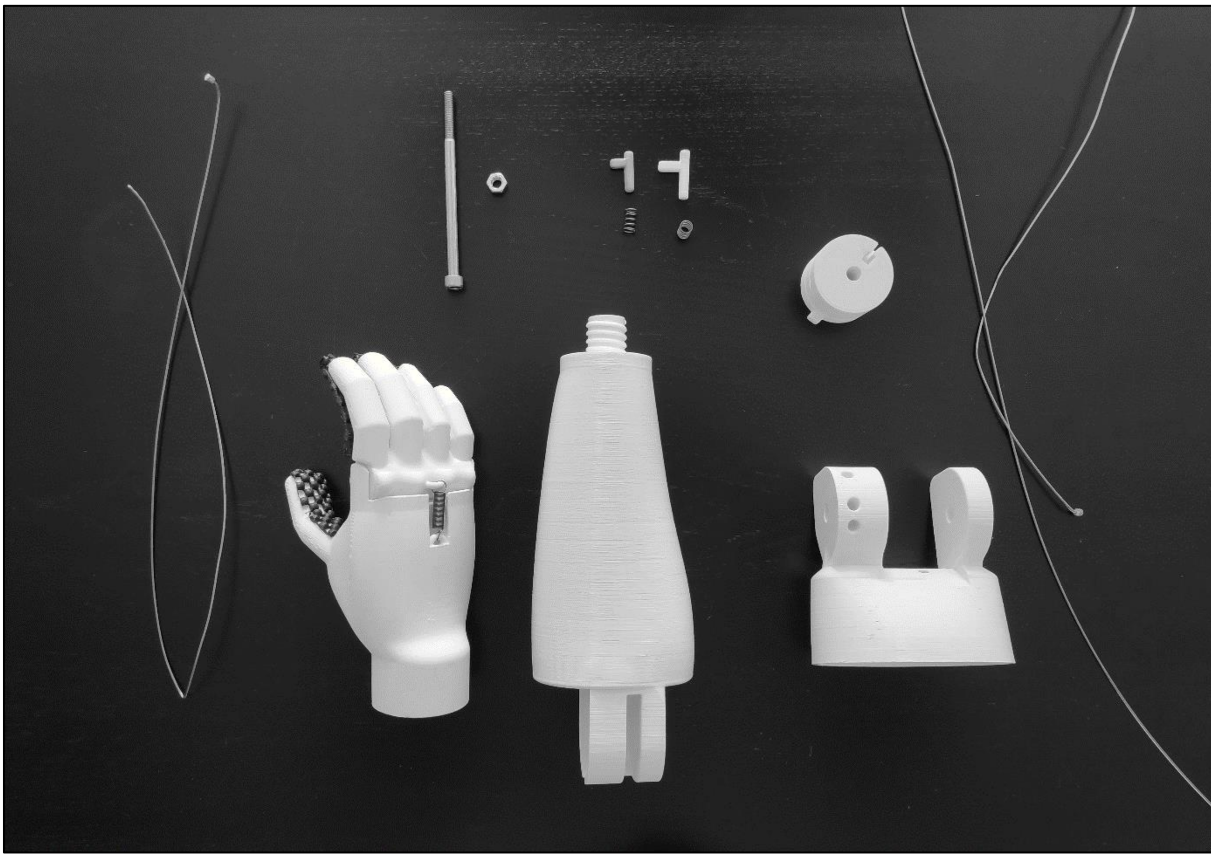






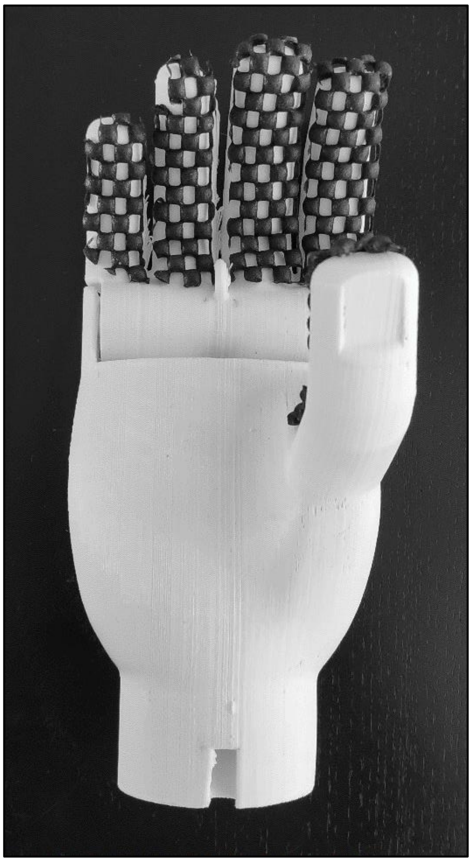


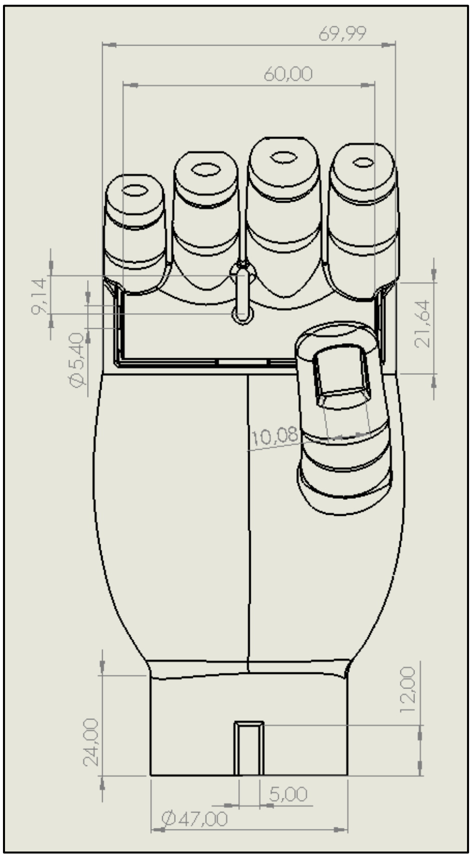


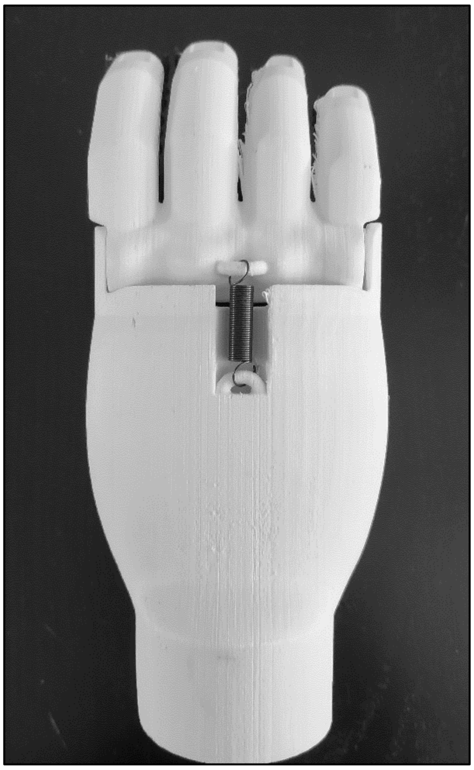


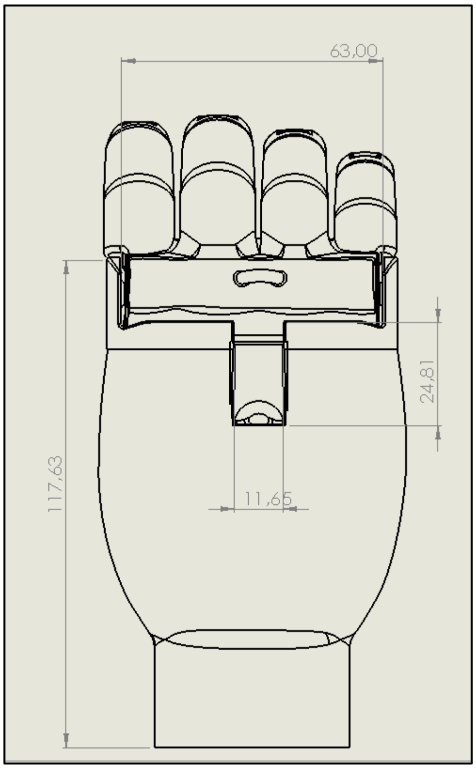
Appendix 2: Hand and wrist joint design

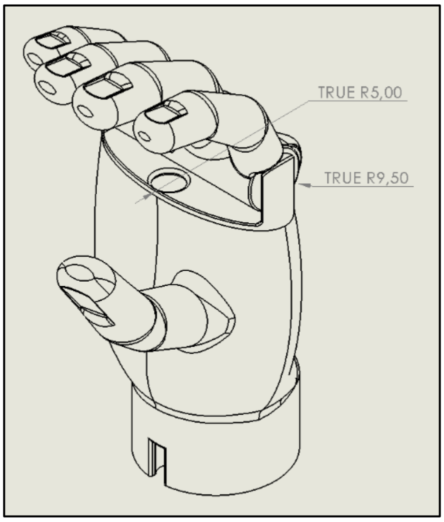
Pictures and drawings (including dimensions) of the hand and wrist joint design are shown in this appendix.

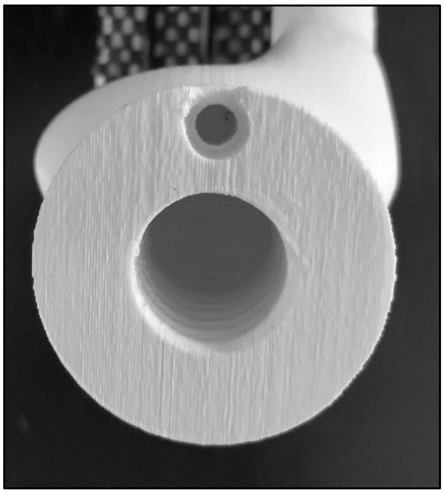


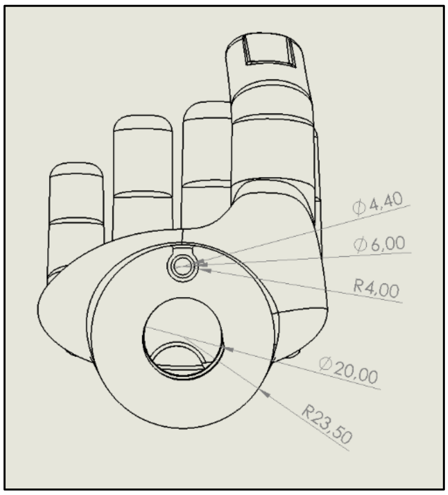






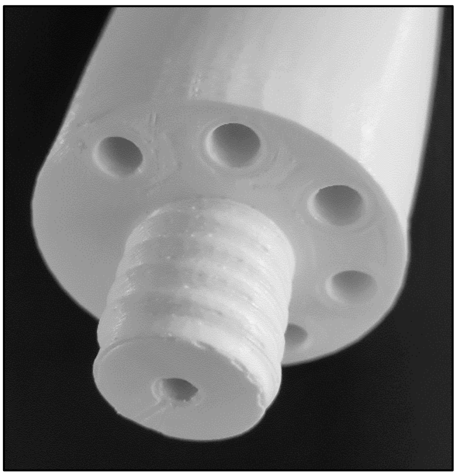


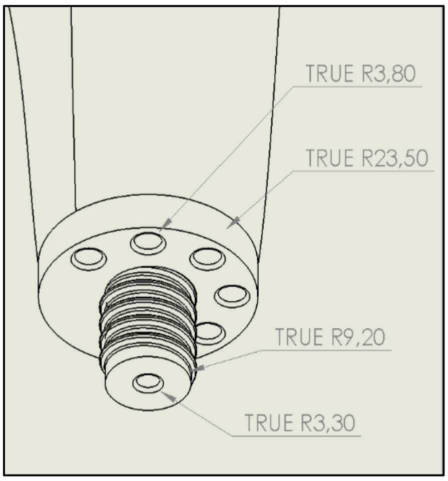


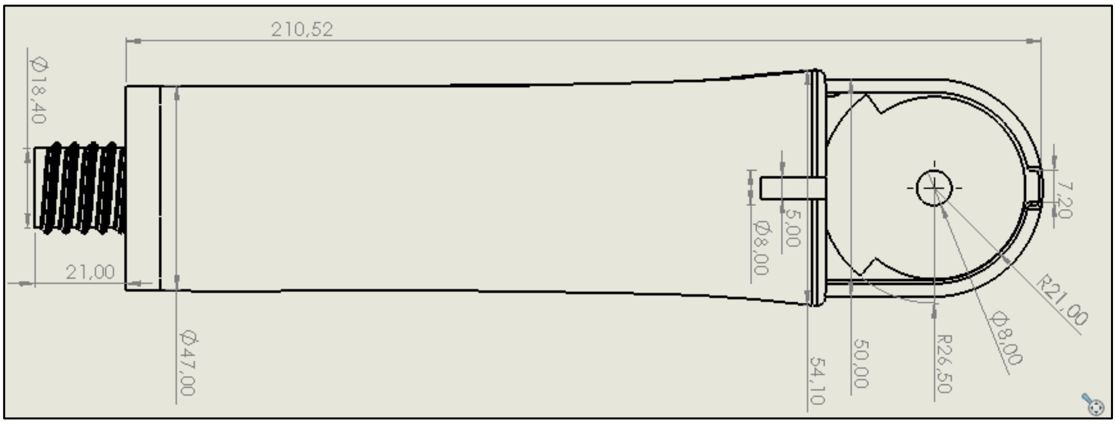


Appendix 3: Lower arm design

Pictures and drawings (including dimensions) of the lower arm design are shown in this appendix.



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Ø47,00
5,00
Ø8,00
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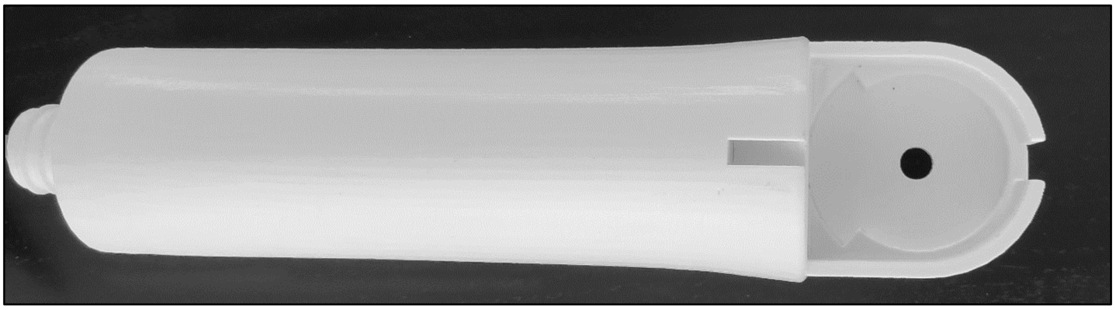
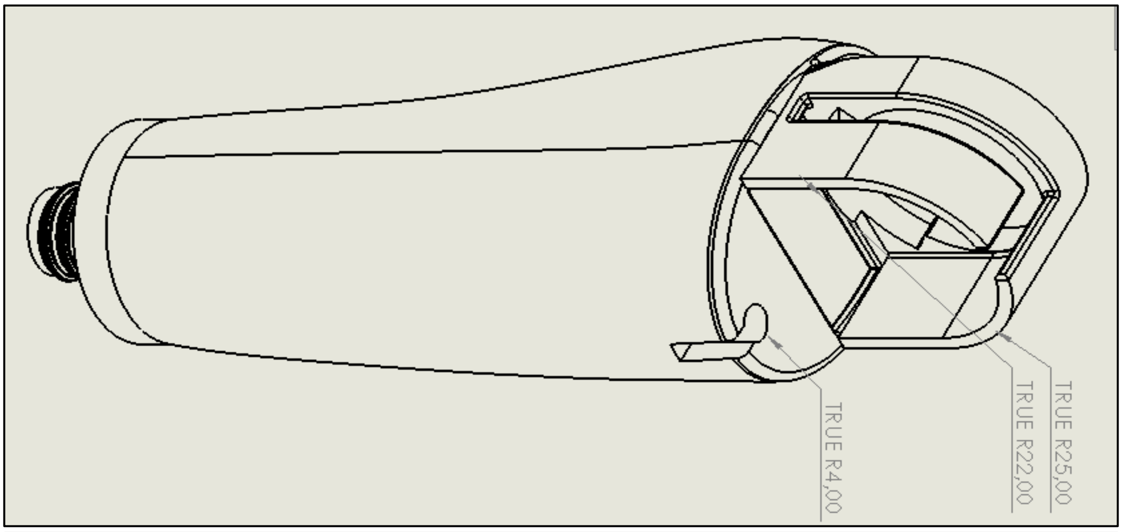
R21,00
Ø8,00
R26,50
50,00
54,10

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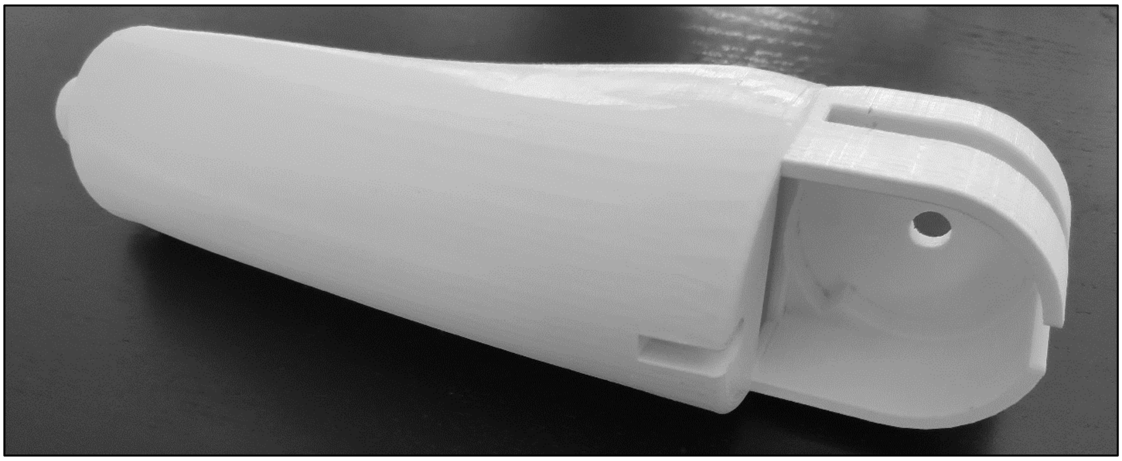
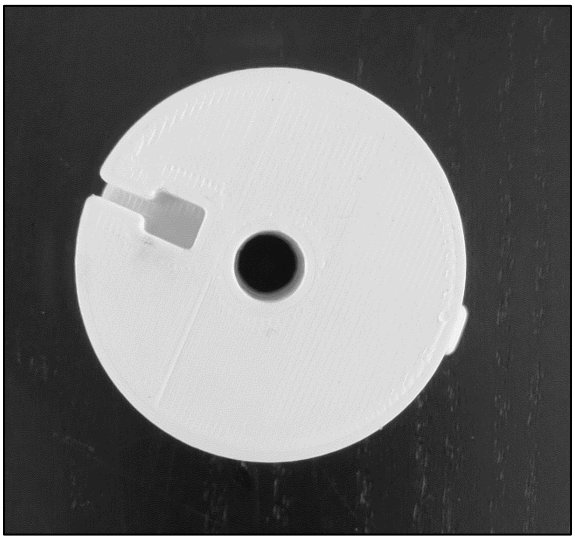
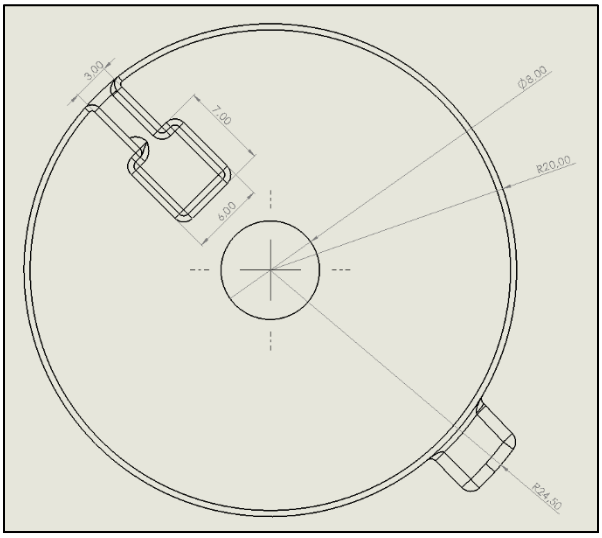
TRUE R22,00
TRUE R25,00

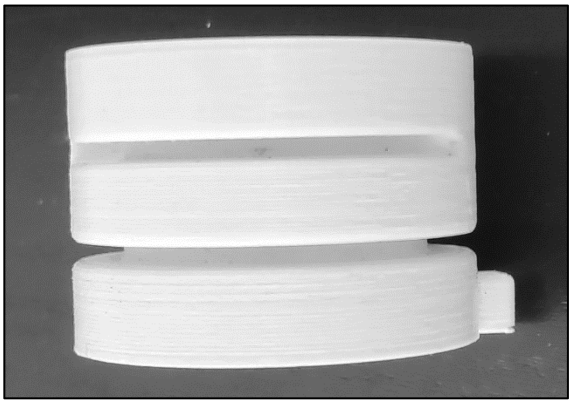


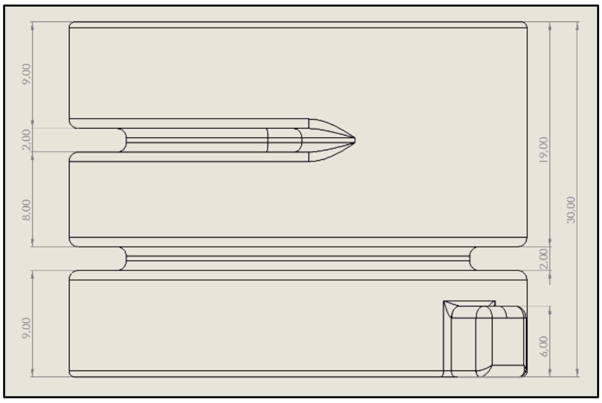
Appendix 4: Elbow pulley design

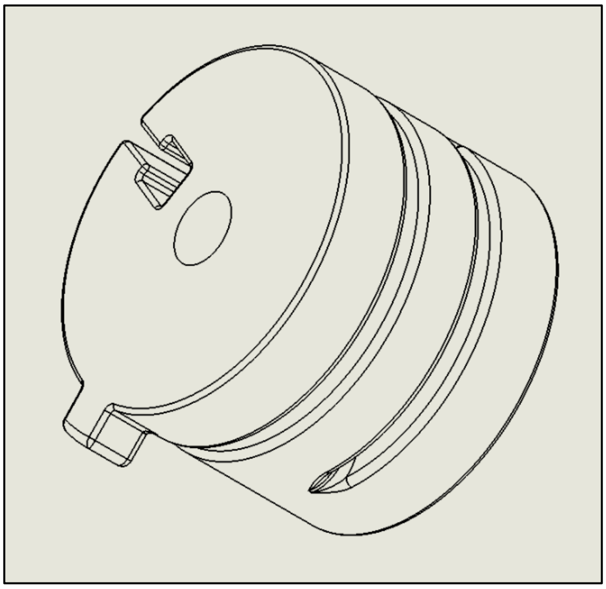
Pictures and drawings (including dimensions) of the elbow pulley design are shown in this appendix.





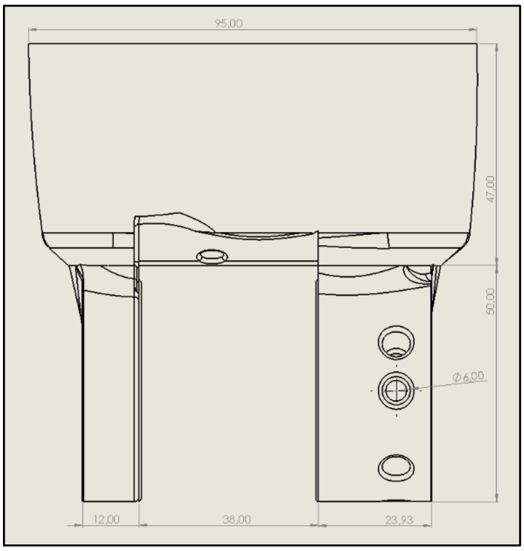


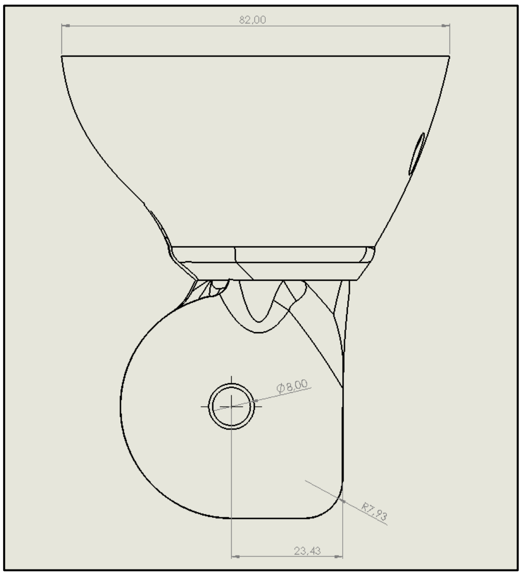


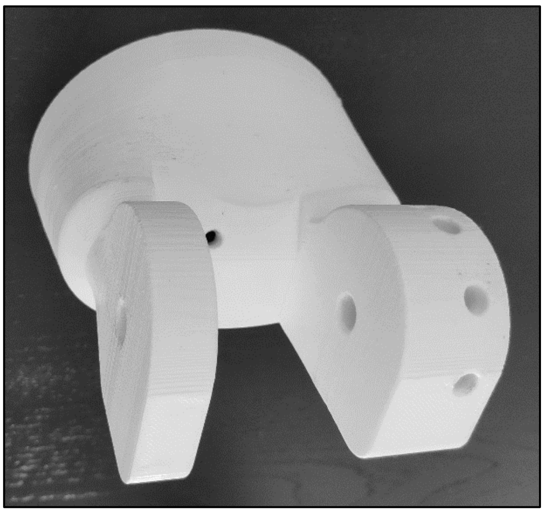


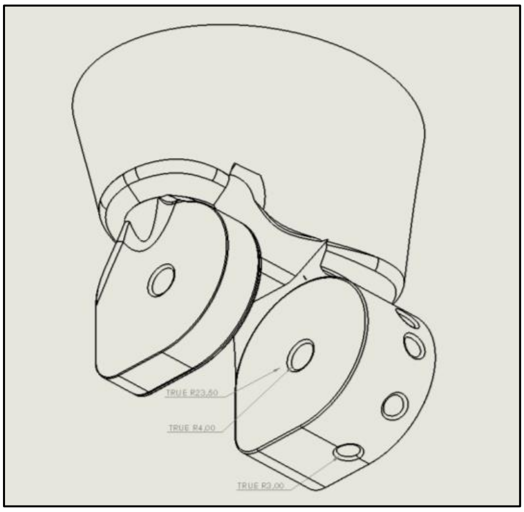
Appendix 5: Upper arm design

Pictures and drawings (including dimensions) of the upper arm design are shown in this appendix.



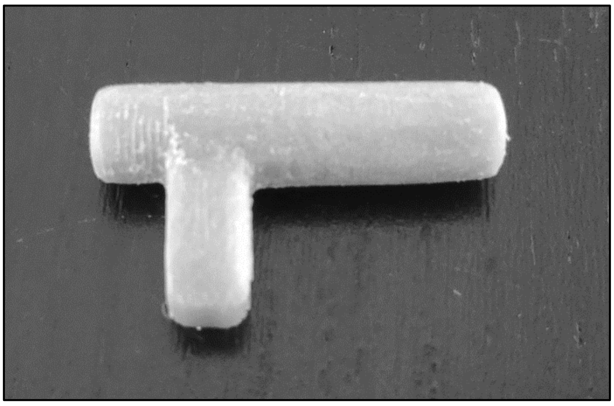


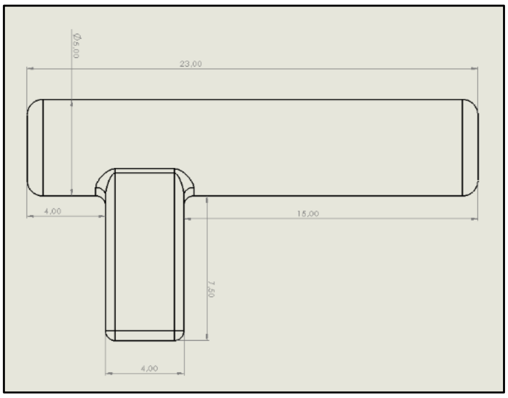


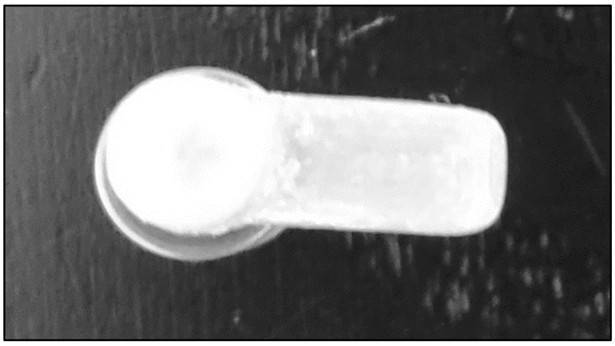


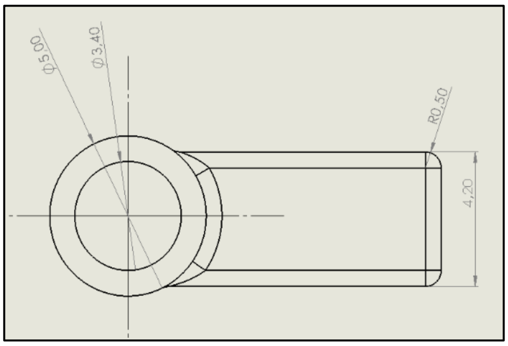
Appendix 6: Wrist joint pin design

Pictures and drawings (including dimensions) of the wrist joint pin design are shown in this appendix.



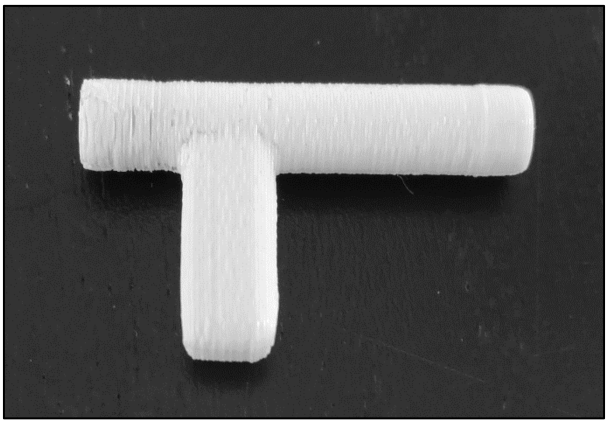


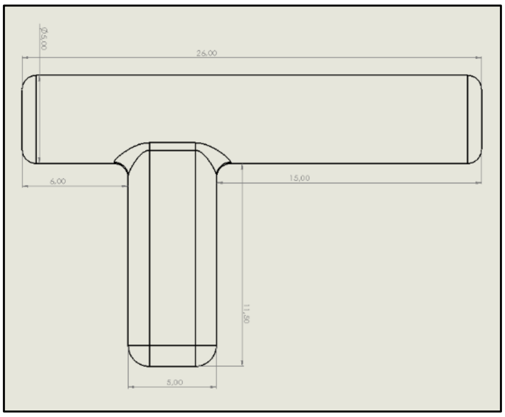


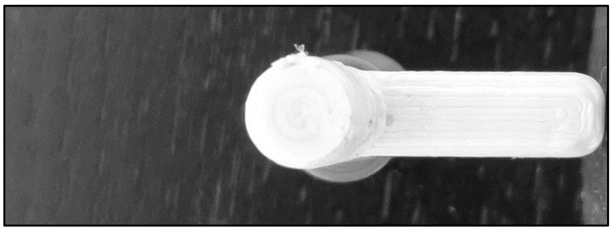


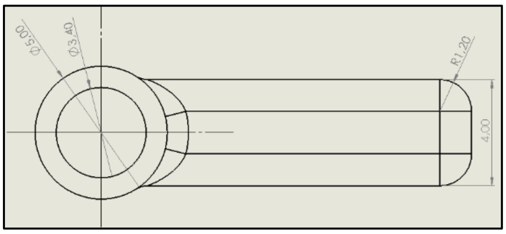
Appendix 7: Elbow joint pin design

Pictures and drawings (including dimensions) of the elbow joint pin design are shown in this appendix.



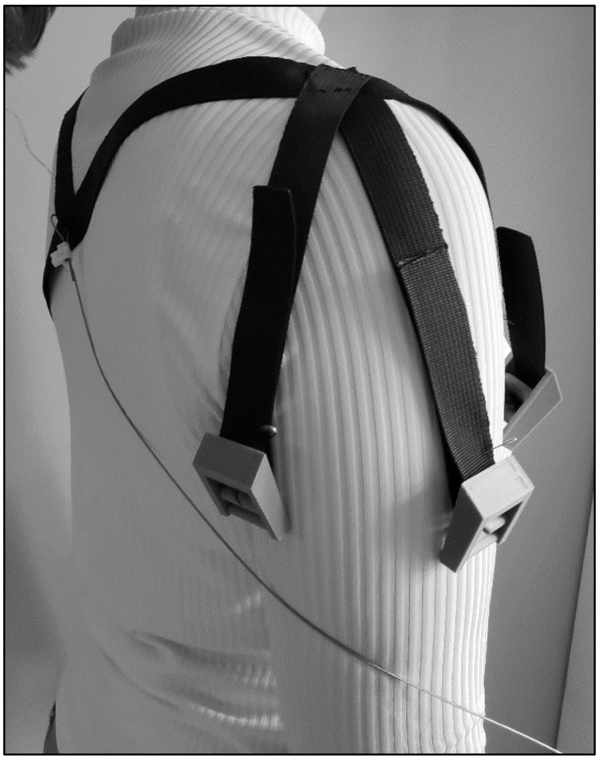


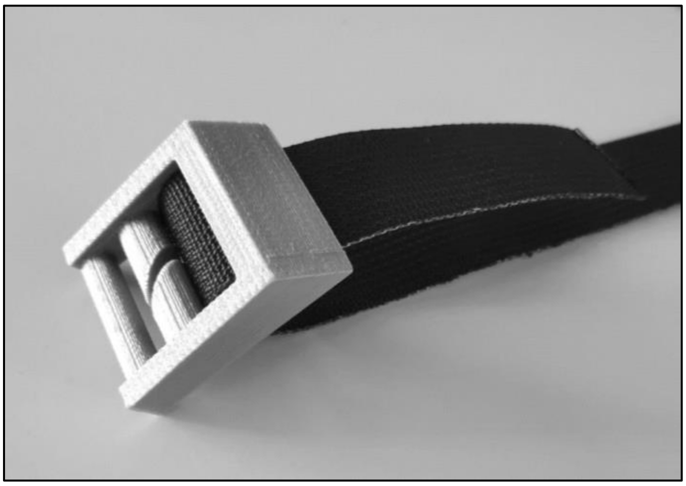




Appendix 8: Harness design

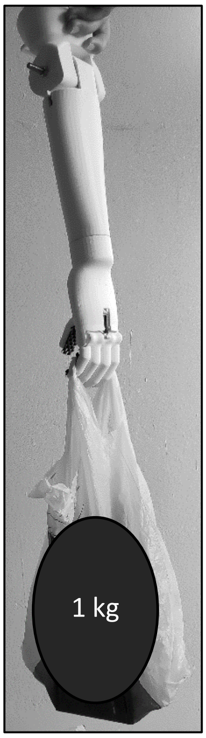
Pictures of the harness design are shown in this appendix.





Appendix 9: Holding a bag of 1 kg with ARM3D

In this appendix pictures of ARM3D carrying a plastic bag filled with a 1 kg bag of sugar in various elbow flexion and wrist joint lock positions are shown.




1 kg

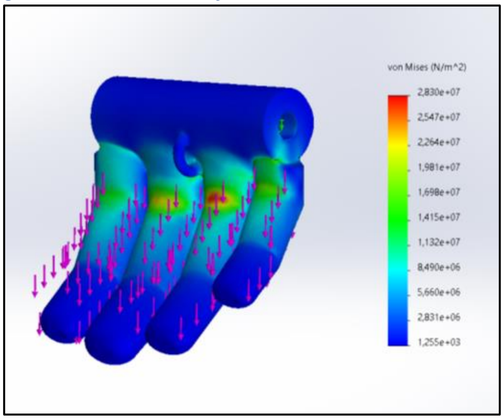

1 kg

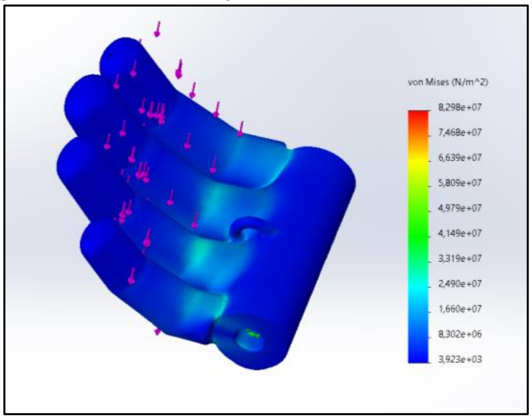
Appendix 10: SolidWorks vonMises stress simulations

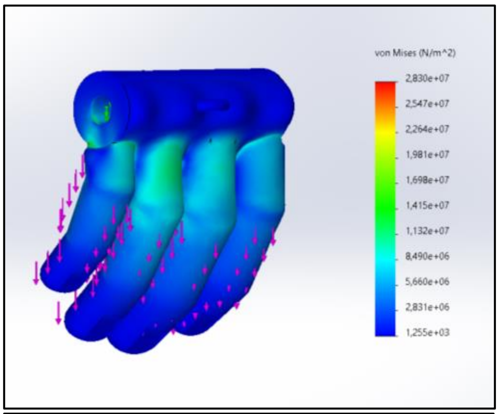
In this appendix vonMises stress simulations on the prosthesis are shown. The first study simulates the vonMises stress on the prosthesis when a load of 5 kg (50 N) is added on the fingers in a 0° as well as in a 90° elbow flexion position. The second study simulates the vonMises stress on the prosthesis when there is 25 N of traction force generated on the upper arm part of the control cable.

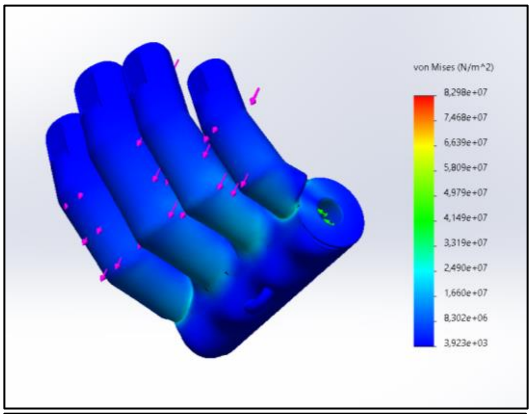
Stress (VonMises) at a 5 kg (50 N) load on the fingers and 0° elbow flexion

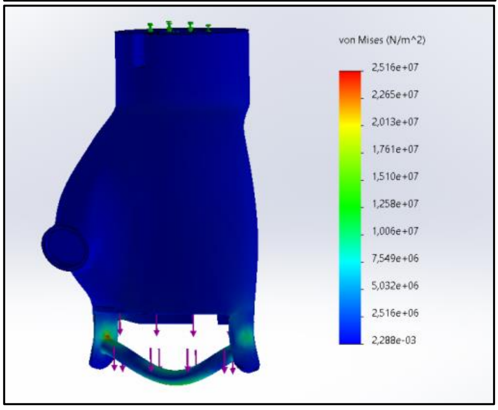
Stress (VonMises) at a 5 kg (50 N) load on the fingers and 90° elbow flexion

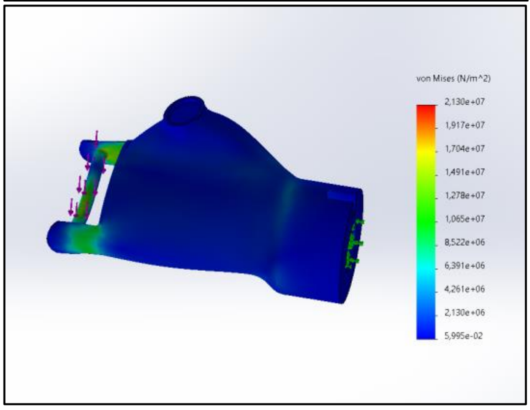


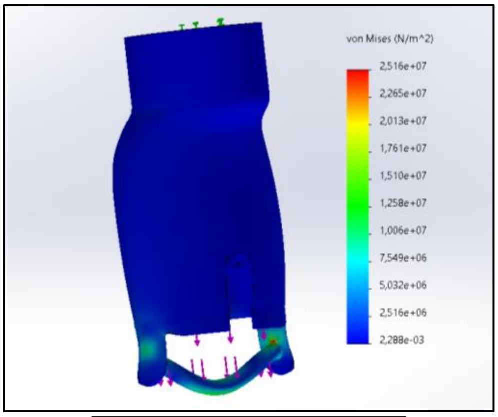








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2,265e+07
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1,761e+07
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1,258e+07
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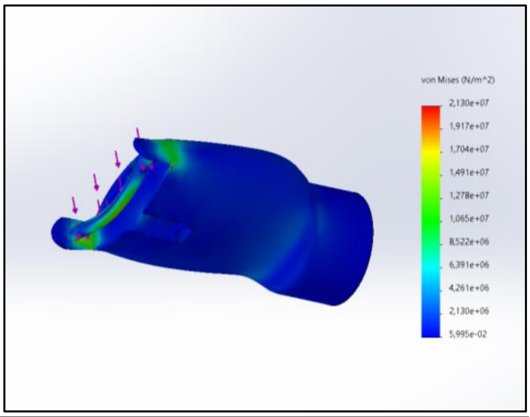
7,549e+06
5,032e+06
2,516e+06
2,288e-03


von Mises (N/m^2)
2,130e+07
1,917e+07
1,704e+07
1,491e+07
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1,065e+07
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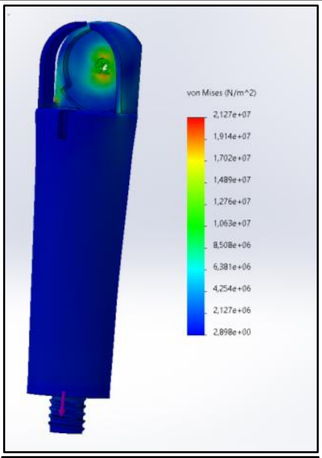
von Mises (N/m^2)
2,127e+07
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1,702e+07
1,489e+07
1,276e+07
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8,508e+06
6,381e+06
4,254e+06
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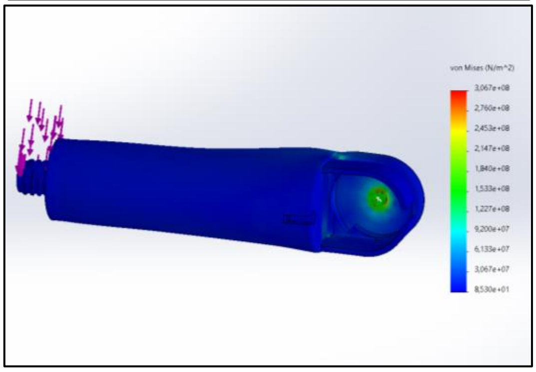
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2,760e+08
2,453e+08
2,147e+08
1,840e+08
1,533e+08
1,227e+08
9,200e+07
6,133e+07
3,067e+07
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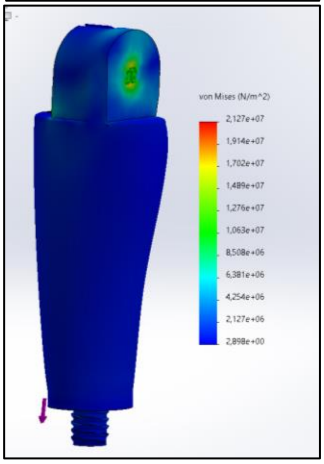
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6,381e+06
4,254e+06
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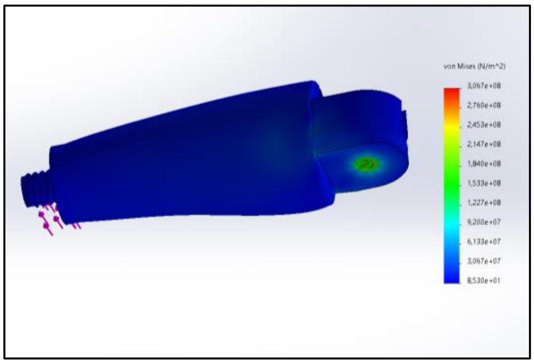
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9,200e+07
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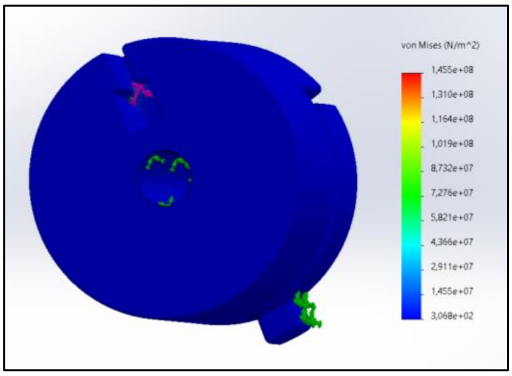
8,530e+01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1,019e+08
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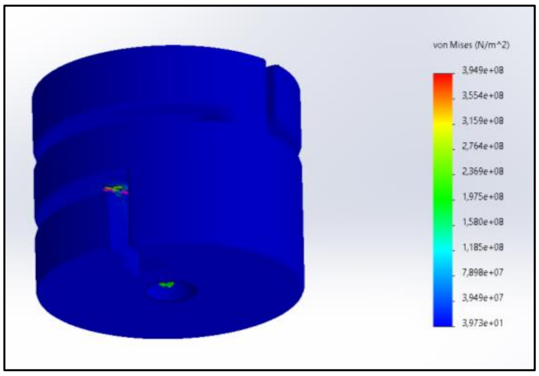
4,366e+07
2,911e+07
1,455e+07
3,068e+02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2,764e+08
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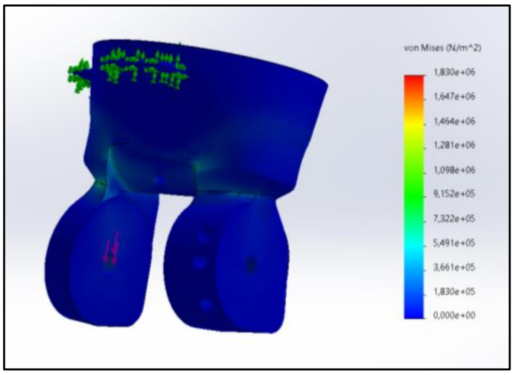
1,580e+08
1,185e+08
7,898e+07
3,949e+07
3,973e+01


von Mises (N/m^2)
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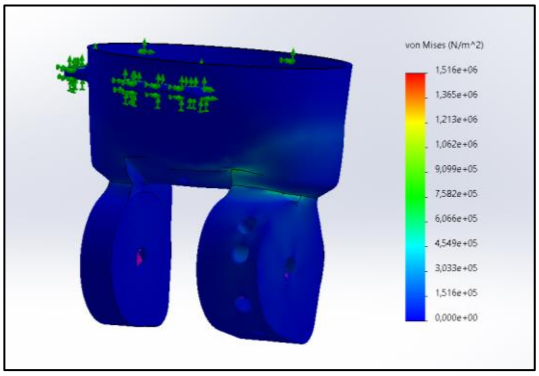
1,647e+06
1,464e+06
1,281e+06
1,098e+06
9,152e+05
7,322e+05
5,491e+05
3,661e+05
1,830e+05
0,000e+00


von Mises (N/m^2)
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1,365e+06
1,213e+06
1,062e+06
9,099e+05
7,582e+05
6,066e+05
4,549e+05
3,033e+05
1,516e+05
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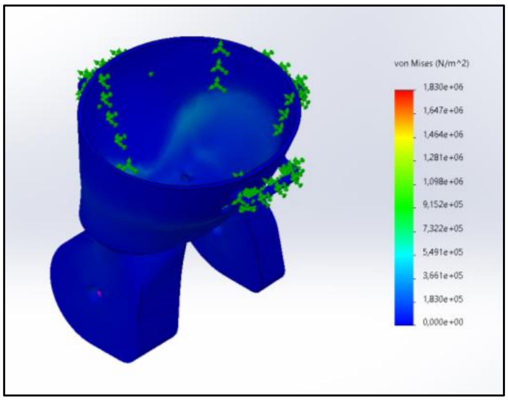
von Mises (N/m^2)
1,830e+06
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1,464e+06
1,281e+06
1,098e+06
9,152e+05
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1,830e+05
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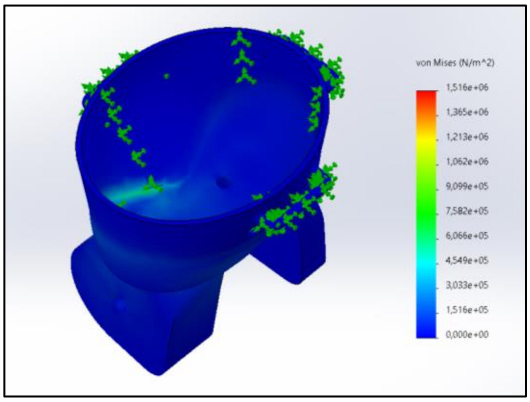
von Mises (N/m^2)
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1,062e+06
9,099e+05
7,582e+05
6,066e+05
4,549e+05
3,033e+05
1,516e+05
0,000e+00

Stress (VonMises) at 25 N traction force on the upper arm part of the control cable