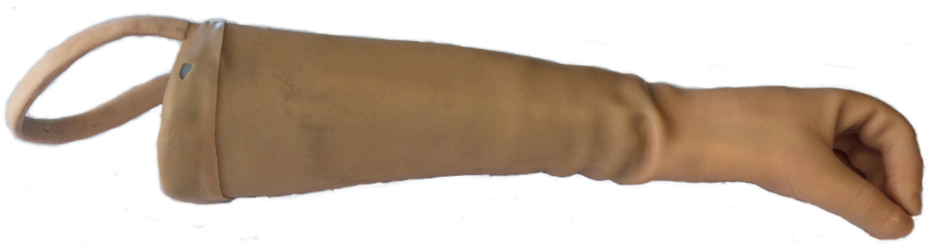
Design of 2^{nd} generation WILMER Open Socket

MSc Thesis Biomedical Engineering

Marina Pogosian

Master of Science Thesis



Delft University of Technology

Delft Institute of Prosthetics and Orthotics

Design of 2nd generation WILMER Open Socket

MSc Thesis

by

Marina Pogosian

in partial fulfillment of the requirements for the degree of

Master of Science

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“Every accomplishment starts with the decision to try”

Gail Devers

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Delft University of Technology
June 15 2015

Marina Pogosian

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Outline

This is a report for my graduation project *Design of* 2^{nd} *generation WILMER Open Socket* for the degree Master of Science, Biomedical Engineering at Delft University of Technology. The study is divided into three chapters. The first chapter is an introduction to the thesis. In the second chapter there is a scientific paper describing the performed study and the final concept. In the third chapter, the Appendix, a more detailed description of the different parts is given.

Chapter 1 - Introduction

In the first chapter, the introduction, a more detailed description about prosthesis in general and the WILMER Open Socket is given. The problem statement and the goal of the thesis are also described here.

Chapter 2 - Scientific paper

Chapter 2 is a scientific paper where the methods and the results are presented. It is a short paper of 16 pages, which gives an overview of the study. The scientific paper is divided into two parts: *design of the locking mechanism* and *design of the socket*. For each part the method, result and discussion are described separately.

Chapter 3 - Appendix

Appendix A describes the current locking mechanism and the different parts. It also describes the fitting procedure of the original WILMER Open Socket. Appendix B gives a short description of the Münster socket's fitting procedure. Appendix C provides a summary of three previous studies done on the WILMER socket and the locking mechanism. Appendix D gives a more detailed description of the design criteria for the locking mechanism and the socket. In Appendix E and F you can find a more detailed description of the final concepts of the mechanism and the socket. The fitting procedure of the new socket is described step-by-step in Appendix F.II. Finally, in Appendix G are the engineering drawings that were used to manufacture the locking mechanism, the H-profile and the wrist joint for the terminal device.

Chapter 1

Introduction

Upper limb amputation causes several functional disabilities and lowers patient's self body image [1]. To replace the missing arm's function and/or appearance, a prosthesis can be connected to the arm remnant. However, many prostheses currently available end up not being used. Studies have shown that 20-40% of the patients do not wear the prosthesis and 40-60% of the wearers do not use the prosthesis for daily activities. Prosthetic users want and expect the prosthesis to look natural, be comfortable to wear and easy to use. These are known as the 3C's; *Cosmesis*, *Comfort* and *Control*. None of the current available prostheses fulfill all these requirements [2].

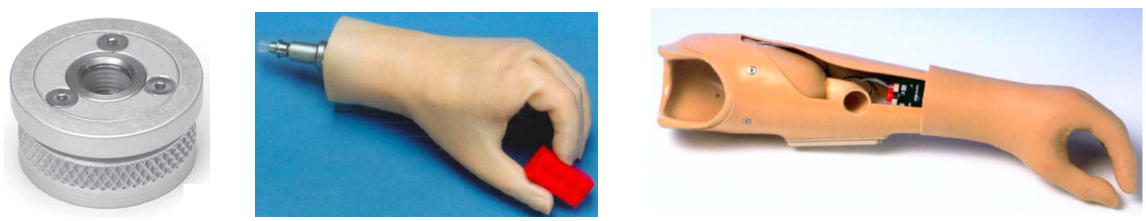
I. Background

The word "prosthesis" comes from the Greek and means to place something to or against [2]. In medicine, prosthesis refers to an artificial device that replaces a missing body part, such as tooth, arm, leg, and it can be used for both functional and cosmetic reasons [3]. One of the earliest known prosthesis is a cosmetic hand prosthesis found 330 B.C, with no moving parts. Currently, a variety of prostheses and sockets are available for clinical application, such as body-powered prostheses, externally powered prostheses, hooks, gloves, passive and active prostheses etc. [2].

With a *body-powered prosthesis*, movement is achieved via a cable/harness control system wrapped around the healthy shoulder or wrist. Body movements, such as shoulder abduction, mechanically activate the prosthetic hand, hook or elbow and provides a pinch grasp for holding objects. *Externally powered prostheses* are electrically powered, i.e. energy is drawn from a battery. These prostheses are controlled by a microprocessor that uses signals from the body. These signals can be captured either by body movement or signals generated by the muscles (myoelectric signals) [2].

I. Below elbow prosthesis

The amputation can be described in different levels and below elbow amputation (transverse defect) ends up in the forearm. A below elbow prosthesis consists of a plastic shell and a wrist joint where the terminal device is attached. The proximal end of the socket is connected to the residual limb and the distal end is connected to the wrist joint with the terminal device. The forearm shell can be connected to the arm remnant either by attaching humeral cuff to the prosthesis by hinges or by self-suspension (like the Münster socket). The wrist joint is usually a passive unit and can allow pronation or supination of the wrist. The terminal device can either be a hook or a hand with voluntary opening (action required from the user to open it) or voluntary closing (action required from the user to close it) [2].



(a) *Wrist joint.* **(b)** *Terminal device -hand.* **(c)** *Below elbow socket*

Figure 1.1: *Below elbow prosthesis: wrist joint, terminal device and the socket [2]*

II. Münster socket

The Münster socket is a below elbow prosthesis, developed by Hepp and Kuhn in 1954, to provide fitting for short and very short below elbow amputees [4]. With this new socket stability was possible to maintain without the use of hinges, split sockets or harness suspension [5]. The Münster socket is a full contact socket, enveloping the epicondyles of the humerus. The socket is self-suspended by a supra condyle rim, thus eliminating the need for harness system [2]. It consists of two parts; a socket and forearm shell of plastic, and it is fitted exactly around the patients arm remnant [6]. A more detailed description of the Münster socket fitting procedure, see Appendix B). Patients with a below elbow defect are usually fitted with self-suspended, full contact prosthesis [2] and the socket commonly chosen is the Münster socket [7]. However, these sockets have three major disadvantages:

- *Difficult donning and doffing:* Since it is a self-suspended socket there is a trade-off between an optimal fixation and donning and doffing of the socket [2]. If the socket is little too big, the muscle cannot fix the socket, which will result in loose socket. If the socket is tight around the limb, donning and doffing of the socket will be difficult [6].
- *Perspiration problems:* The complete envelopment of the residual limb causes perspiration problems [7].
- *Difficult fitting:* Fitting procedure is difficult. It requires a lot of skill and experience to produce these sockets [7].

Figure 1.2: *The Münster socket [2, 5]*

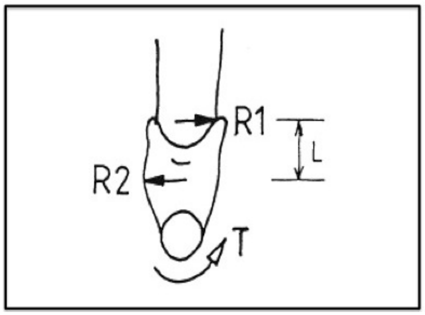
III. WILMER Open Socket

At Delft University of Technology, the WILMER Open Socket was developed for below elbow amputees. The socket is designed based upon study of the forces transmitted between the prosthesis and the residual limb (Figure 1.3). It is an open socket that uses minimal area for fixation of the socket and leaves 75% of the skin uncovered. This way the skin breathe freely and perspiration problems can be minimized [2].

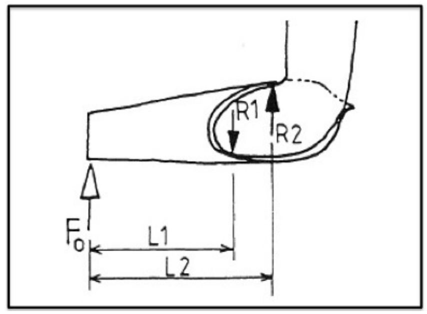
The socket consists of two rings enveloping the residual limb, one located more proximal on the limb and more one distal integrated with the forearm shaft. Together with the condyle brace a complete socket is formed of stainless steel tubes. The tubes are covered with soft foam, which makes it more comfortable to wear. To protect against abrasion the foam is covered with a polyurethane coating. Figure 1.4 shows how the two rings and the condyle brace fitted onto the residual limb [2, 7, 8].

The WILMER Open Socket allows easy donning and doffing, and a good fixation to the residual limb by making the socket adjustable. With a locking mechanism the condyle brace can be locked into different positions. When pushing the button on the top of the prosthesis the locking mechanism can be released and adjusted into one of the 20 different positions with intervals of 1.3mm (Figure 1.6). A proximal movement of the V-shaped condyle brace creates extra space in two directions; distal-proximal to give space to the residual limb and medial-lateral to give space to the condyles (Figure 1.5). The locking mechanism provides the prosthetic users an adjustable socket and a more personalized fit. The amputees can tighten and loosen the socket anytime needed. The adjustable socket is especially good for children since they constantly grow [2, 7, 8].

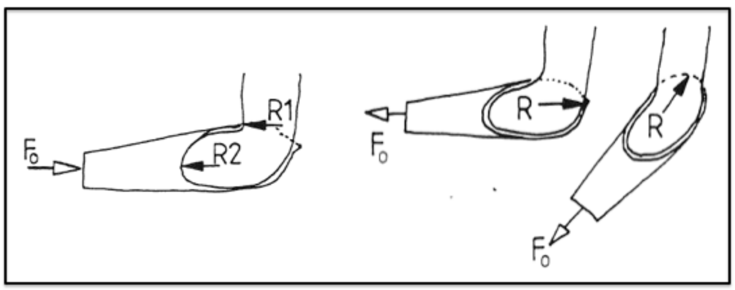
The open socket is fitted directly onto the patient. This reduces the number of steps needed to produce a more correctly fitted read-to-wear socket [7]. A more detailed description of the fitting procedure, see Appendix A.II. Originally the WILMER socket was designed for children. The socket has been tested on several children in age between two and sixteen by Walta et al (1989), and according to this study the open socket was highly appreciated by most of the children [7].



(a) *Torque acting on the socket.*



(b) *Radial force acting on the socket.*



(c) *Axial force acting on the socket.*

Figure 1.3: *Forces acting on the socket [7].*

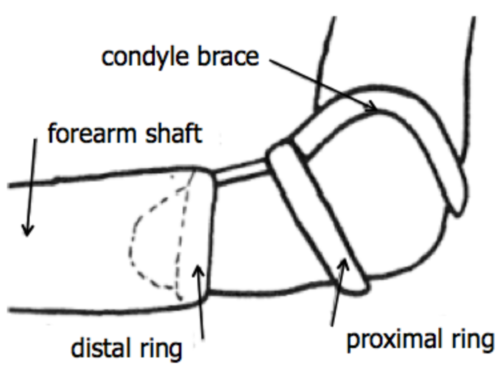
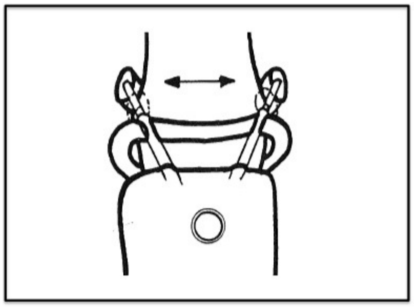
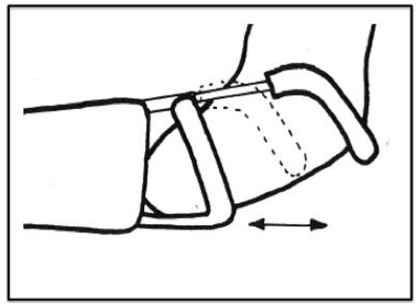


Figure 1.4: *The distal - and proximal ring, and the condyle brace fitted onto the residual limb [7].*

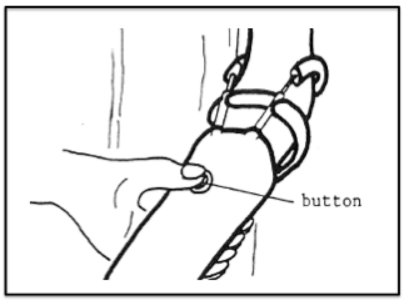


(a) *Space created in the medial-lateral direction.*

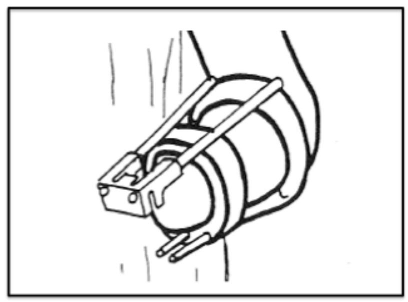


(b) *Space created in the distal-proximal direction.*

Figure 1.5: *Condyle brace in the open position [7].*



(a) *Pushing button to release the locking mechanism.*



(b) *The distal and proximal ring, and the locking mechanism fitted onto the limb.*

Figure 1.6: *Locking mechanism [7].*

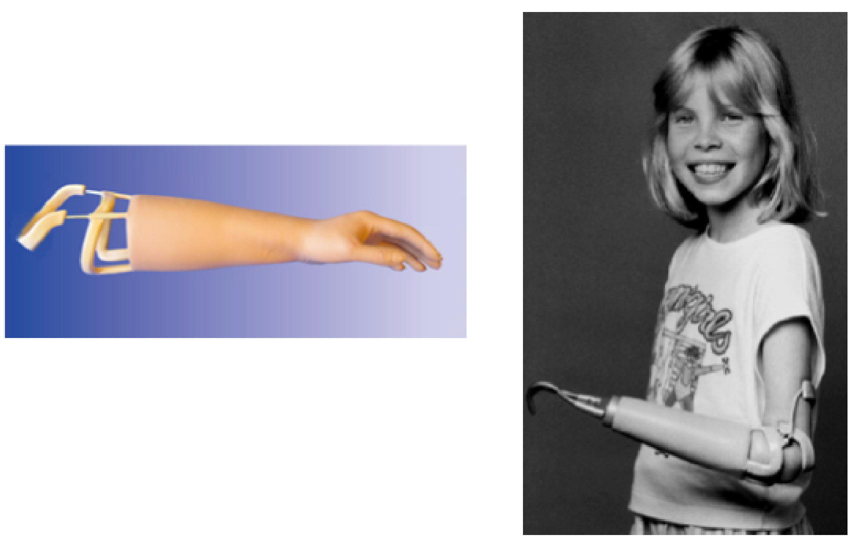


Figure 1.7: *The WILMER Open Socket [2]*

II. Problem statement

Although the WILMER Open Socket has many advantages, feedback from prosthetic users has shown that there are areas for improvement. The users have indicated that the foam covering the stainless steel rings gives the socket a bulky structure, and they would like to have a socket that fits closer to the skin and is more aesthetically pleasing (Figure 1.8) [8]. Furthermore, the relative large locking mechanism requires sufficient space inside the socket and can result in a much thicker prosthesis. This is a problem, especially for small children or patients with long and thick residual limbs. When the residual limb is long and thick, the locking mechanism will be on the residual limb instead of in front of the limb, thus the socket needs to be thicker so that there is space for the locking mechanism (Figure 1.9) [9].

The disadvantages of the WILMER Open Socket (bulky design and large locking mechanism) degrade the cosmetic value of the prosthesis and can result in reduced wearing. Therefore, it is of great importance to improve these disadvantages.

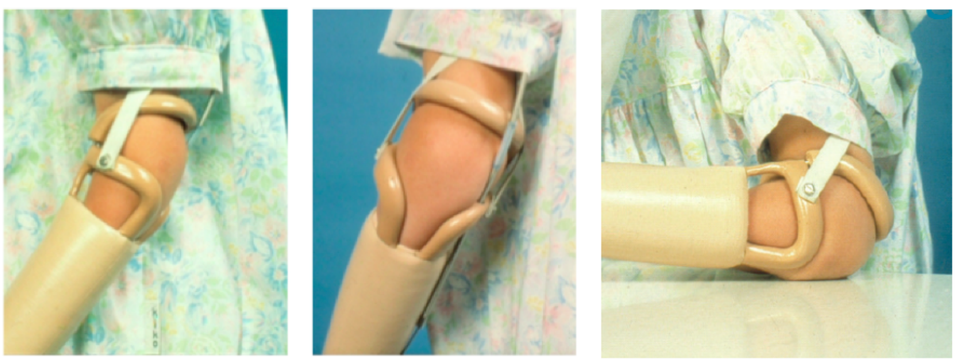


Figure 1.8: *WILMER Open Socket's bulky structure: the stainless steel tubes covered with foam [8]*

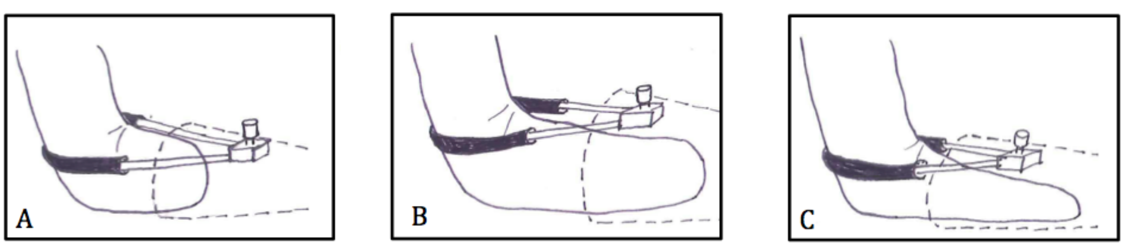


Figure 1.9: *Disadvantage of the current locking mechanism. A: Short residual limb and the locking mechanism in front of the limb. B: Long and thick residual limb,the locking mechanism is on top of the limb, and a thicker socket is needed. C: Long and small residual limb, the locking mechanism is on the top of the limb but a thicker socket is not needed.*

III. Thesis objectives

The study was aimed to design a new WILMER Open Socket that fits closer to the skin and is more aesthetically pleasing. Furthermore, a new design was also made for the locking mechanism to reduce the thickness of the socket. The goal was to:

1. *Design a new WILMER socket:*
    - with less bulky design,
    - a smoother transition between the socket and the limb, and
    - keep the advantages the existing socket has: minimized perspiration problems, easy donning and doffing, and adjustability.
2. *Design a new locking mechanism:*
    - that does not make the socket thicker for children or patients with long and thick residual limbs.

Hence, the study was divided into two parts: *design of the locking mechanism* and *design of the socket*. In the following, a scientific paper describing the performed study and the final concept is presented.

Chapter 2

Scientific paper

.

Design of 2^{nd} generation WILMER Open Socket

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Abstract

Upper limb amputation causes several functional disabilities and lowers patient's self body image. At Delft University of Technology the WILMER Open Socket has been developed for below elbow amputees. It allows easy donning and doffing, and minimizes perspiration problems by leaving 75% of the skin uncovered. However, the relative large locking mechanism and the bulky structure of the socket degrade the cosmetic value of the prosthesis and can result in reduced wearing. The aim of this study was to design a new WILMER socket that fits closer to the skin and is more aesthetically pleasing. A new design was also made for the locking mechanism to reduce the thickness of the socket for children and patients with long and thick residual limbs. The final design and the prototype of the locking mechanism have a height of 7.2mm, which means that a reduction of 6.8mm has been achieved. The new WILMER socket was made out of stainless steel wire mesh. The socket has a smoother transition between the arm and the limb (<5mm) (original 11mm) and a forearm shell covering the mesh gives a more lifelike appearance. The socket is also adjustable and it can easily be donned and doffed. The new WILMER Open Socket can have a great value for below elbow amputees. A more natural looking prosthesis improves the cosmetic value and can result in increased wearing. However, there are still steps in the fitting procedure that need to be simplified and evaluation of the comfort, permeability and patient's opinion on the design is needed.

Keywords: *WILMER Open Socket; Locking mechanism; Prosthesis; Below-elbow prosthesis; Arm amputee.*

I. Introduction

Upper limb amputation causes several functional disabilities and lowers patient's self body image (Dudkiewicz et al, 2004). The most common socket currently used for a below elbow defect is the Münster socket (Walta et al, 1989), which has several disadvantages including perspiration problems due to the complete envelopment of the residual limb and difficult donning and doffing of the socket (Plettenburg, 2006). Moreover, the fitting of the socket is difficult, a lot of skill and experience are needed to produce these sockets (Walta et al, 1989).

In 1985, at Delft University of Technology, the WILMER Open Socket was developed for children with a below elbow defect (Walta et al, 1989). This

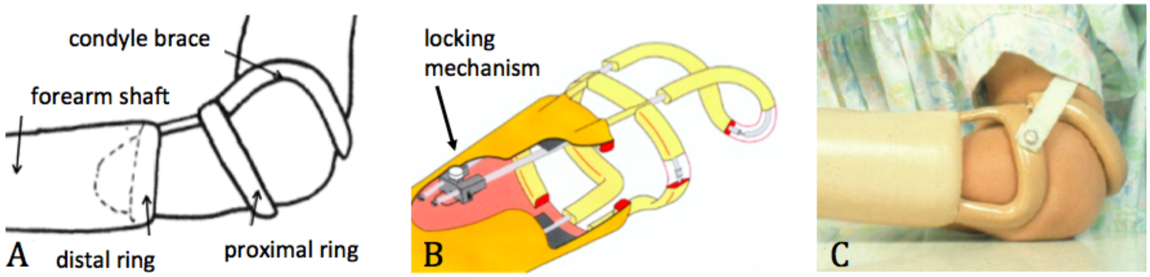


Figure 2.1: A: The distal - and proximal ring, and the condyle brace of the current WILMER Open Socket, which is fitted onto the residual limb (Walta et al, 1989). B: The locking mechanism and the braces (Plettenburg, 2006). C: The WILMER socket's bulky structure (Wong, 2008). The stainless steel tubes covered with foam have a thickness of approximately 10-12mm.

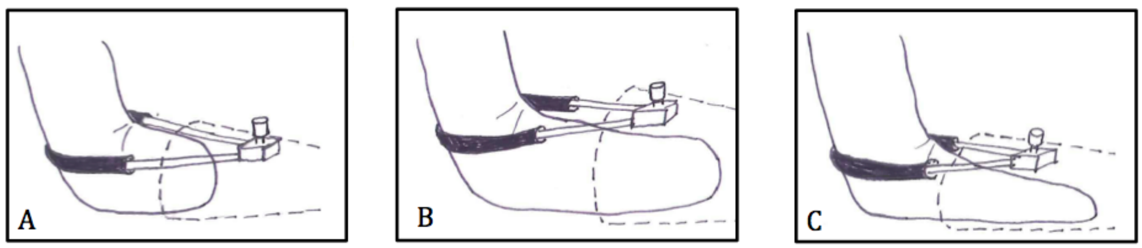


Figure 2.2: The disadvantage of the original locking mechanism. A: Short residual limb and the locking mechanism in front of the limb. B: Long and thick residual limb, the locking mechanism is on top of the limb, and a thicker socket is needed. C: Long and small residual limb, the locking mechanism is on the top of the limb, but a thicker socket is not needed.

socket allows easy donning and doffing, and minimizes perspiration problems by leaving 75% of the skin uncovered. It consists of two rings enveloping the residual limb, one located more proximal on the limb and one distal integrated with the forearm shaft. Together with the condyle brace a complete socket is formed of stainless steel tubes (Figure 2.1A). With a locking mechanism on the top of the prosthesis, the condyle brace can be locked in one of the 20 different positions with intervals of 1.3mm (Figure 2.1B). A proximal movement of the V-shaped condyle creates more space in the media-lateral direction for easier donning and doffing and a better fit around the limb. The locking mechanism provides the prosthetic users an adjustable socket and a more personalized fit. The amputees can tighten and loosen the socket anytime needed (Plettenburg, 1998; Plettenburg, 2006; Walta et al, 1989).

Although the WILMER Open Socket has many advantages, feedback from prosthetic users have shown that there are areas for improvement. The users have indicated that the foam covering the stainless steel rings gives the socket a bulky structure (Figure 2.1C) and they would like a socket that fits closer to the skin and is more aesthetically pleasing (Wong, 2008). Furthermore, the relative large locking mechanism requires sufficient space inside the socket and can result in a much thicker prosthesis (Figure 2.2). This is a problem, especially for small children or patients with long and thick residual limbs (Plettenburg, 2014). These disadvantages degrade the overall cosmetic value of the prosthesis and result in reduced wearing.

The primary aim of this study was to design a new WILMER Open Socket that fits closer to the skin and is more aesthetically pleasing. The goal was to design a socket that keeps the advantages the existing socket has i.e. easy donning and doffing, adjustable and minimized perspiration problems, but with less bulky design and smoother transition between the socket and the limb. Furthermore, a new design was also made for the locking mechanism to reduce the thickness of the socket for children and patients with long and thick residual limbs. Hence, the study was divided into two parts; *design of the locking mechanism* and *design of the socket*. In the following sections (method, result and discussion) these two parts will be described separately.

II. Material and Method

The new locking mechanism and the socket were designed based on the 3C's; *Cosmisis*, *Comfort* and *Control* (Plettenburg, 2006). Hence, the mechanism and socket should look as natural as possible, it should be comfortable to wear and easy to use. In the this section the design process of the locking mechanism and the socket is described separately.

II.1 Locking mechanism

II.1.1 Design criteria

The main objective for the locking mechanism was to design a new mechanism that reduces the thickness of the socket, especially for children. Since the WILMER Open Socket was originally designed for children, the design requirements are calculated for a 14-year-old child. This age has been chosen because a *child* is defined as a human being aged 14 and under, and the age group 15 to 24 years is defined as a *youth* (Angel, 1995). For a more detailed description of the criteria, see Appendix D.I.

1. Height less than 7.5mm
The current WILMER locking mechanism has a height of 14mm, which is the mechanism's biggest issue and causes a thicker socket (Plettenburg, 2014). The maximum height of the new design was calculated by taking the difference between the thickness of the residual limb and a healthy forearm. The anthropometric data used was from 13-14 years old healthy children (Jakovljevic et al, 2011) (Canadian Summary, 2011/2012). The maximum height of the locking mechanism was set to less than 7.5mm.

2. Strength higher than 600N
The design should be strong enough to withstand the body weight of the user. The average weight for children at age 14 years is 60kg (Fryar et al, 2012). Hence, the locking mechanism should be able to withstand a force of 600N.

3. Weight less than original mechanism (<35g)
The weight of the new design should be less than the original mechanism, which is approximately 35g for a child version (50g for an adult). Even though the weight of the existing mechanism is not an issue, a light weight socket is always desirable to reduce skin pressure and allow natural handling of the prosthesis (Walta et al, 1989). Thus, the requirement was set to less than 35g.

4. Possible to V-shape
The locking mechanism should be possible to V-shape. As mentioned earlier, the V-shaped condyl brace create more space in the medial-lateral direction and allows easier donning and doffing (Walta et al, 1989).

5. Other requirements
The new mechanism should be *easy to lock and unlock*, and this should be possible to do with only *one hand*. *No parts should stick out* from the prosthesis, because it does not look natural and it can damage the clothes.

II.1.2 Design approach

In a previous study done by Bos et al (2012) a new locking mechanism was designed. Their design used a sideways movement of the button to unlock the system (Figure 2.3). This was combined with the main working principle of the original mechanism i.e. knife and teethed bar (see Appendix A.I), but instead of one button and housing they used two separate systems. The teeth of the bars were kept to the original height (0.8mm) but the diameter

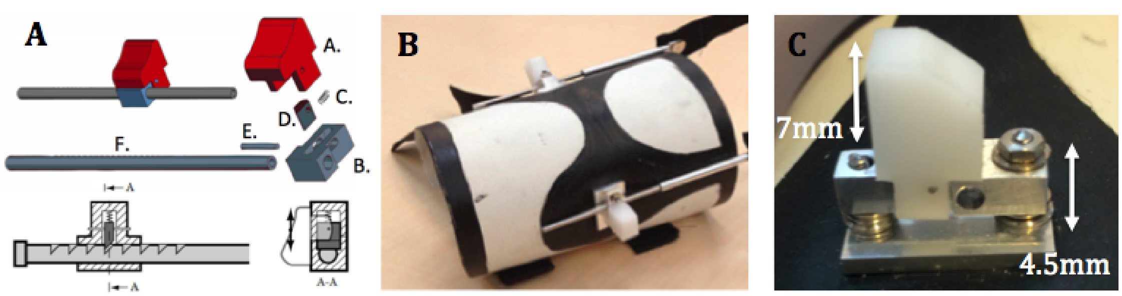


Figure 2.3: *The 3D model and prototype of the locking mechanism designed by Bos et al (2012). A: The 3D model. A) Button B) Housing C) Spring D) Knife E) Pin F) Teethed bar. B: The mechanism attached to a mock-up prosthesis. C: The height of the mechanism is 4.5mm and the button is approximately 7mm.*

Table 1: *Parameters of the original, the design by Bos et al (2012) and the new locking mechanism for the WILMER Open Socket.*

Original	Bos et al (2012)	New
• One housing	• Two housing	• One housing
• Push button	• Sliding button	• Push button and sliding motion
• Operated with one finger	• Operated with two fingers	• Operated with one finger
• Button do not stick out	• Button stick out	• Button do not stick out
• Bar diameter 3.9mm	• Bar diameter 2.5mm	• Bar diameter 2.5mm
• Teeth height 0.8mm	• Teeth height 0.8mm	• Teeth height 0.8mm

was reduced to 2.5mm instead of 3.9mm (the original bar diameter). The final design had a height of 4.5mm, which means that a reduction of 9.5mm was achieved compared to the original locking mechanism. Although Bos et al (2012) reduced the height significantly, there are still limitations in their design. Since the sliding motion was created by sliding movement of the button with the thumb and index finger, this part had to stick out from the socket. Two separate housings were also used, which is more difficult to operate with one hand. Hence, to design the new locking mechanism the advantages and drawbacks of both locking mechanisms were investigated (Bos et al (2012) and the original) and different parameters were selected (Table 1).

II.1.3 Conceptual design

Working principle

The final design of the locking mechanism uses the idea of altering a sliding motion to unlock the system. This was chosen because when the knife locks the teethed bar on the side instead of the bottom, a larger reduction in the high can be achieved (Figure 2.4A). This principle was then combined with the main working principle of the original locking mechanism with a knives, teethed bars and one housing. A push-button was used to create the sliding motion. When the button is pressed the two sliders with knives moves sideways and unlock the system (Figure 2.4C). One housing with a button was used because it is easier to operate with one hand and the push-button can be sanded so no part will stick out from the socket, like the original mechanism.

Dimensioning

The bar diameter was selected to 2.5mm and the height of the teeth to 0.8mm (Figure 2.4B). The contact area between the teethed bar and the knife was 1.35mm^2 and when one lock is loaded with a force of 300N the stress in the teethed bar becomes 222MPa. Since this value does not exceed the yield stress for stainless steel type 303 and 304 (original bars and knives were made of these materials) of 240MPa (Fisher, 2014), these dimensions were chosen for the bars.

The new button has almost the same design as the original system, but with a 45-degree angle to move

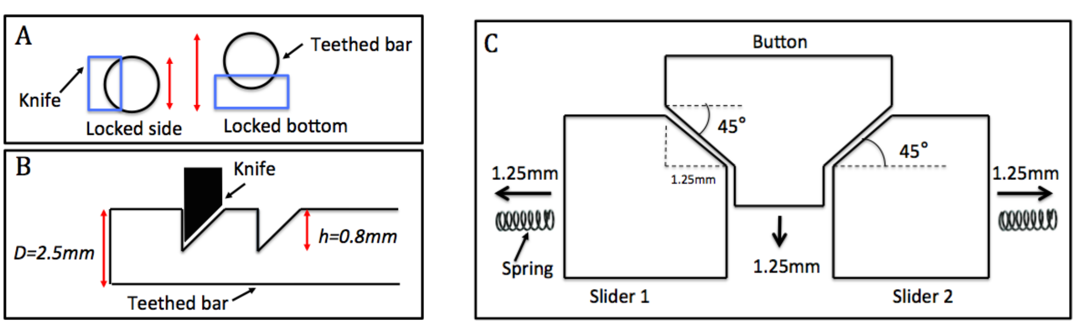
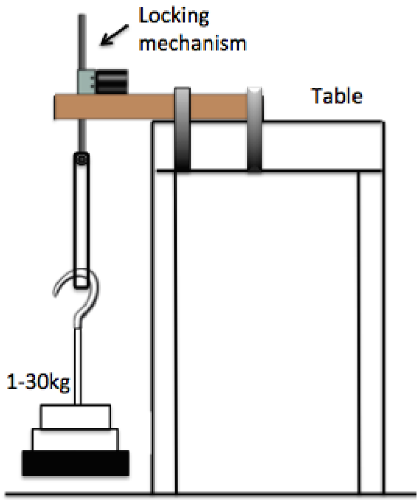


Figure 2.4: The working principle of the new locking mechanism. A. The two locking cases: the knife locking the teethed bar from the side (new mechanism) and the bottom (original mechanism). B: The teethed bar and the knife. The bar has a diameter of 2.5mm and teeth height of 0.8mm. C: Sliders and the button. When the button is pressed 1.25mm the two sliders move 1.25mm in the horizontal direction and unlock the system. Springs are attached to the sliders and when the button is released, the sliders return to their original position and lock the system.



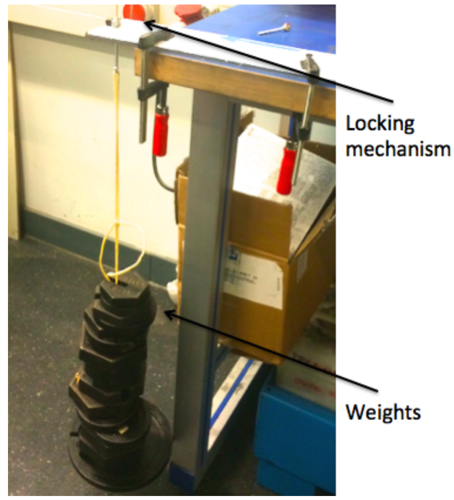


Figure 2.5: *The ocking mechanism strength test setup. The mechanism is fixed to a table and with a metal hook connected with a wire to one of the locks, weights (1-30kg) were loaded on the mechanism.*

the sliders horizontally. The angle of the top edge of the sliders has also a 45-degree angle and when the button is pressed 1.25*mm* in the vertical direction, the sliders will move 1.25*mm* horizontally and unlock the system. Springs were attached to the sliders and when the button is released the sliders move to their original position and lock the system (Figure 2.4C).

II.1.4 Strength test

To evaluate the strength of the locking mechanism strength test was performed. The test setup and equipment can be seen in Figure 2.5. The locking mechanism was fixed to a table and a metal hook was connected to one of the locks with a wire. The metal hook was used to load one of the locks with weights (1-30kg). The test started with 1kg and slowly more weights were added, up to 30kg. The test condition was to stop the test either when the lock broke or if 30kg was reached. Since the prosthesis was designed for children up to 14 years old with average weight of 60kg (Fryar et al, 2012), each lock should be able to withstand a tensile force of 300N (Design criteria I.1).

II.2 Socket

II.2.1 Design criteria

The main objective for the socket was to design a socket that keeps the advantages the existing socket has (minimized perspiration problems, easy donning and doffing, adjustable) but with less bulky design and a smoother transition between the socket and the limb. A list of requirements was made, which the new socket design should fulfill. For a more detailed description of the requirements see Appendix D.II.

1. Smooth transition between the socket and the limb
The new socket should have a smooth transition between the socket and the limb. The original socket has big and bulky braces, and there is a large difference in height between the arm and the socket (approximately 10-12mm). The design requirement for the new socket was to have a transition between the socket and the limb less than half the difference of the current socket, i.e. less than 5*mm*.

2. Sufficient ventilation of the socket
The current WILMER socket uses the minimal area for fixation of the socket and leaves 75% of the skin uncovered to minimize perspiration problems (Plettenburg, 2006). To keep this advantage the new design should either leave 75% of the skin uncovered or be made of breathable material. However, Wong (2008) found in a research study that many users still complain about perspiration and heat problems (Wong, 2008). Therefore, it was decided to make the new socket out of breathable material to minimize these problems.

3. Adjustable
Since children constantly grow it is desirable to have the socket adjustable. This is one of the advantages

with the existing WILMER socket and it should also be kept in the new design. With the locking mechanism the braces should be adjusted into one of the 20 different positions with intervals of 1.3*mm* (Walta et al, 1989).

4. Easy donning and doffing
The patient should be able to easily don and doff the new prosthesis using one hand and they should be able to self attach the socket to the limb.

5. Lightweight
The new socket should be lightweight to reduce skin pressure and create natural handling of the socket (Walta et al, 1989). The child version of current open socket weighs approximately 200g (Wong, 2008). The goal of the new design was to keep the weight equal or less than the current socket.

6. Strength higher than 600N
As mentioned before (for locking mechanism), the new design should be strong enough to withstand the users body weight, which is 60kg for a 14-year old child.

7. Other requirements
The new socket should be made out of *comfortable material* and it should be *lifelike*, i.e. it should have skin color, be made of soft material and no part should stick out. The socket should also be possible to fit in standard prosthetic facility (see Appendix A.II).

II.2.2 Design consideration

When designing a prosthetic socket there are some important aspects that need to be considered, such as the forces between the socket and the limb. The skin and underlying soft tissue of the residual limb are not adapted to shear process, high pressure and other irritations (Mak et al, 2001). Forces directed in the plane of the skin (shear forces) often lead to skin damage, thus should be avoided. To reduce the forces between the socket and the limb, the center of mass should be kept as proximal as possible (Figure 2.6A). Furthermore, the reaction forces between the socket and the limb are directly proportional to the mass of the prosthesis. A reduction of the socket's total mass also reduces the reaction forces, even when the position of the center of mass is not changed (Figure 2.6B) (Plettenburg, 2006).

Another important consideration is the pressure distribution between the socket and the residual limb (Mak et al, 2001). The fitting contact pressure should be evenly distributed without sudden changes in magnitude (Plettenburg, 2006).

II.2.3 Conceptual design

Material
In two previous Master thesis done at Delft University of Technology (TU Delft) the WILMER Open Socket was redesigned to improve the cosmetic value of the prosthesis. In the first study by Wong (2008), the socket and the two braces were made out of stainless steel metal foam (see Appendix C.I). Ravensbergen (2010) did a research on different materials applicable in the prosthetics field and the

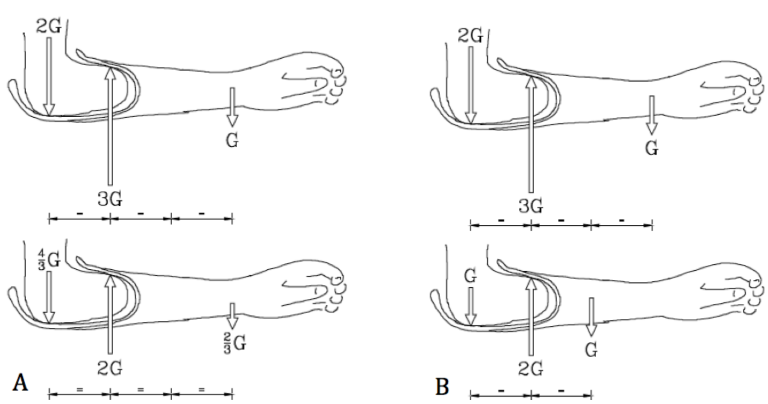


Figure 2.6: *Reaction forces between the socket and the residual limb. A: A shift of the center of mass in the proximal direction reduces the reaction force between the socket and the limb B: A reduction of the overall mass of the prosthesis reduces the reaction force between the socket and the limb. (Plettenburg, 2006).*

material that fulfilled her design requirements the most was stainless steel wire mesh. The socket material stainless steel metal foam, which was proposed by Wong (2008), was rejected by Ravensbergen (2010) due to high cost. In both studies a prototype was not built due to time constraints (see Appendix C).

The material stainless steel wire mesh proposed by Ravensbergen (2010) was also chosen in this study for the new socket design because it has several advantages; it is thin (approximately 0.8mm), easy to deform, has low cost (Salomons Metalen, 2015), and when the mesh edges are connected it is strong and stiff. TU Delft has also prior experience with this material in the WILMER elbow orthoses, and it does not cause any skin reaction when the material is in direct contact with the skin (Kalkman et al, 1978), (Gelderblom, 1980).

The selected wire mesh for the new WILMER Open Socket has a wire thickness of $0.37mm$ and mesh width of $1.218mm$, which gives a transmittance of 59% (Salomons Metalen, 2015). This size has been chosen because in a previous study done at TU Delft, it was shown that the highest permeability for the stainless steel wire mesh was obtained for a wire diameter of $0.4mm$ and a mesh width of $1.42mm$, which gave a transmittance of 60% (Gelderblom, 1980). In order to use the stainless steel wire mesh as a prosthetic socket, it has to be bent into the right shape. This has been done with a plaster-model of the residual limb (Figure 2.17a and b).

Wire mesh connecting methods
To connect the wire mesh edges different methods have been tested, including H-profile, soldering (soft and hard soldering), point welding and different adhesive. The optimal method was selected based on the design criteria for the socket. The chosen connecting method should be equal or stronger than the wire mesh, the material should be biocompatible with the skin and the mesh edges should be easy to connect.

Wire mesh sharp edges
To cover the sharp wire mesh edges different types of plastic were tested (Figure 2.7): two different types of u-profile plastic (A and C), a rubber u-profile (B) and a thin plastic sheet (E). Other methods that also have been tested were: foam (D), wire mesh folded around the socket (F) and a plastic tube (G). The optimal method was selected based on the thickness it added to the socket. The thickness of the wire mesh socket and the material around the sharp mesh edges should be less than $5mm$.

II.2.4 Strength test

Wire mesh connecting methods
To select the optimal wire mesh connecting method strength tests were performed. The wire mesh samples had a width of 4cm and the length of 20cm. For each method two samples were made and two different strength tests were performed; shear and tensile strength. For the shear strength test the wire mesh edges were connected with 1cm overlapping and in the tensile strength test the edges were connected end-to-end. The point welding method could only be tested for shear forces since it is not possible to point weld the wire mesh end-to-end. Strength tests were not performed on the H-profile because it has already been done by Ravensbergen (2010).

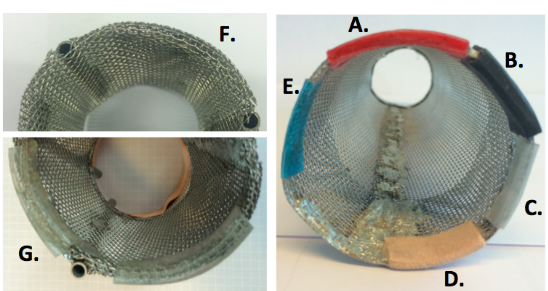


Figure 2.7: Different methods to cover sharp mesh edges. A) plastic u-profile B) rubber u-profile C) plastic u-profile D) foam E) plastic sheet F) bent wire mesh G) plastic tube

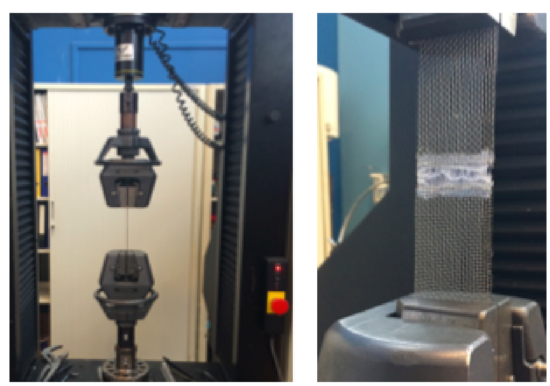
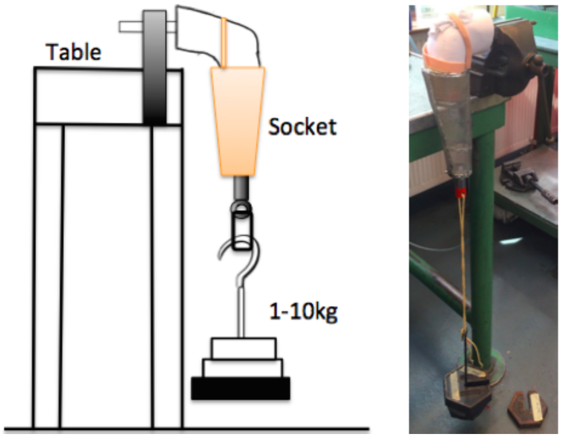
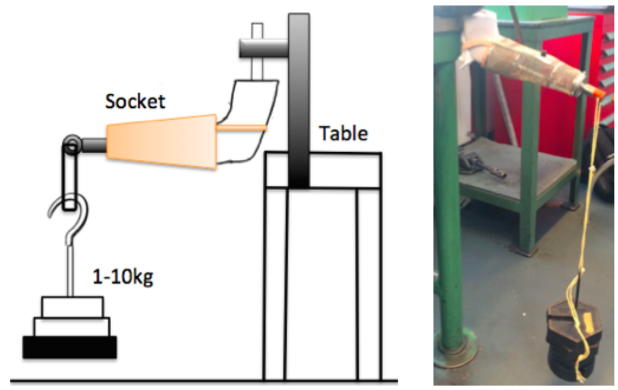


Figure 2.8: A wire mesh sample is connected with clamps to the test bench INSTRON 5500R to test the strength of the different connecting methods.



(a) Test 1: Axial force is applied to the socket, which test the situation "holding a bag with 0-degree shoulder abduction".



(b) Test 2: Radial force is applied to the socket, which test the situation "holding a bag with 90-degrees elbow flexion".

Figure 2.9: *The wire mesh socket strength test setup. The mesh socket is inserted into a plaster model of the residual limb that is fixed to the table. With a metal hook weights (1-10kg) was loaded on the socket.*

The tests were performed with the test bench INSTRON 5500R. Figure 2.8 shows the wire mesh sample fixed to the test bench with two clamps. The elongation rate could be adjusted with a computer device. To get a clear load-extension graph the elongation rate was selected to be 5*mm* per minute. The result was fed back to the computer for visualization of the force and the displacement. All data processing was performed with MATLAB R2013b (Mathworks).

Socket

To evaluate the strength of the socket two different strength tests were performed and the test setup and equipment can be seen in Figure 2.9. In both tests the socket was inserted into a plaster-model of the residual limb fixed to the table. Similar to the locking mechanism strength test setup a metal hook was loaded with weights, and it was connected to the distal end of the socket with a wire. With the new socket the prosthetic user should be able to carry a bag of 10kg or more. The minimum weight was chosen to 10kg because the new socket is designed for children and 10kg is a reasonable weight for a 14-year-old child to carry with the prosthetic limb. The test started with 1kg and slowly more weights were added, up to 10kg. The test condition was to stop the test when the socket starts to deform visually, the condyle brace broke or when 10kg was reached. If the socket deformed before 100N was reached, stainless steel plates were soldered to the socket to increase the stiffness and the same test was performed again. In the first test an axial force was applied to the socket and in the second test a radial force was applied to the socket (Figure 2.9). The two strength test setup was based on two common ways to carry a bag; 0-degree shoulder abduction i.e. the arms straight down (test 1), and 90-degrees elbow flexion (test 2) (Figure 2.10).

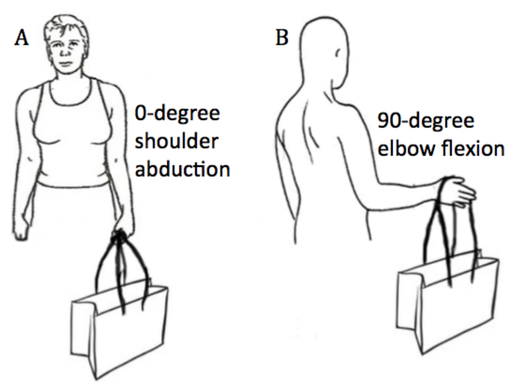
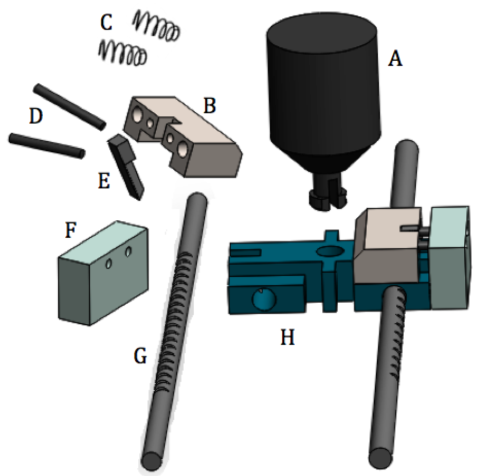


Figure 2.10: *Two common ways to carry a bag. A: 0-degree shoulder abduction. B: 90-degrees elbow flexion.*

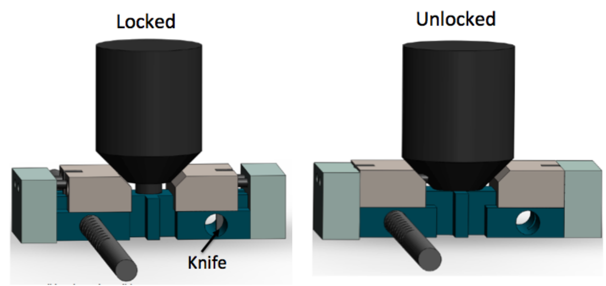
III. Result

III.1 Locking mechanism

The final model of the locking mechanism consists of 8 components. Figure 2.11 shows the 3D image of the whole model and the different parts and Figure 2.12AC shows the final prototype. The first component is the housing, which was made out of



***(a)** The different parts of the new locking mechanism. A) Button B) Slider C) Springs D) Pins E) Knife F) Support for the springs and pins G) Teethed bar H) Housing.*



***(b)** 3D image of the whole model. When the button is pressed the two sliders with the knives move* 1.25*mm in the horizontal direction and unlock the system.*

***Figure 2.11:** 3D image and the different parts of the new locking mechanism.*

PVC, like the original system, and when it is heated to approximately 60-degrees it can be V-shaped. The second, third, forth and fifth components are the sliders (2 needed, made of aluminum), knives (2 needed, made of stainless steel), pins (4 needed, made of aluminum) and the springs (4 needed). The knives, pins and slider are three separate components, but should be glued together. The pins are used to hold the sliders on its place. Two supports for the springs and the pins (made out of aluminium) are connected on each side of the housing and when pressing the button the two sliders will move 1.25*mm* in the horizontal direction and the pins will slide into the support (Figure 2.11b). The teethed bars had the same dimension as the design by Bos et al (2012), thus their produced parts could be used (Figure 2.4B). A more detailed description of the different part of the new mechanism, see Appendix E.I.

The final design has a height of 7.2*mm* and a total weight of 9g, which is within the requirements. The difference in height between the new and original locking mechanism was 6.8*mm* (Figure 2.12). The result of the strength test showed that one lock could withstand more than 300N tensile force. A total of

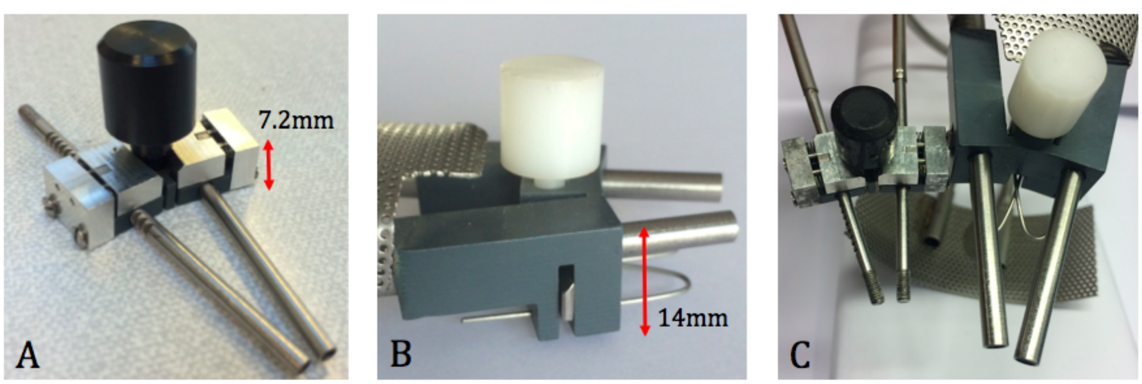
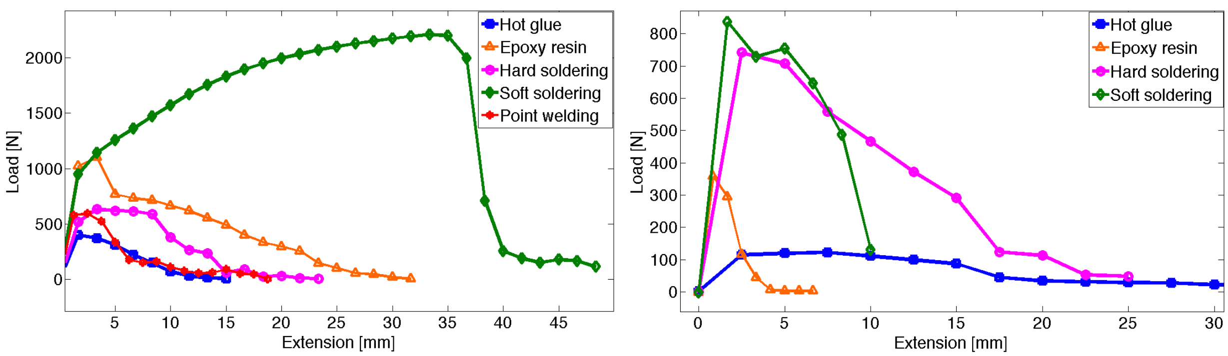


***Figure 2.12:** The final prototype of the new and the original locking mechanism for WILMER Open Socket. A: Prototype of the new locking mechanism with height 7.2mm. B: Prototype of the original locking mechanism with height 14mm. C: The new and the original locking mechanism.*

Table 2: *Mean maximum force for the different wire mesh connecting methods before breaking.*

Test	Shear force [N]	Comment	Tensile force[N]	Comment
Hot glue	400	Connection broke	120	Connection broke
Epoxy resin	1202	Connection broke	522	Connection broke
Hard soldering	643	Connection broke	420	Connection broke
Soft soldering	2110	Wire mesh broke	1050	Connection broke
Point welding	614	Connection broke	-	-
H-profile (Ravensbergen, 2010)	1800	Wire mesh broke	-	-



(a) *Shear strength* **(b)** *Tensile strength*

Figure 2.13: *Graphical representation of the mean shear and tensile strength forces [N] for the different wire mesh connecting methods (hot glue, epoxy resin, hard and soft soldering and point welding) before breaking.*

30.5kg (305N) was loaded on one of the locks without breaking. The new locking mechanism can be operated with one hand and it can be adjusted into one of the 20 different positions with intervals of 1.3*mm*.

III.2 Socket

III.2.1 Strength tests

Wire mesh connecting methods

Strength tests were performed (shear and tensile strength) to select the optimal wire mesh connecting method and the result can be seen in Table 2 and Figure 2.13. The different connecting methods were hot glue, epoxy resin, hard and soft soldering, point welding and H-profile. Table 2 shows the mean maximum shear and tensile forces and Figure 2.13 shows the load-extension graph of the mean shear and tensile forces for the different connecting methods. As can be seen in Figure 2.13 and Table 2, the method that had the lowest shear and tensile forces was the hot glue (400N and 120N). In the soft soldering shear strength test the wire mesh broke and not the connection at 2110N (Figure 2.14B). This was also the case for the H-profile strength test in the study of Ravensbergen, (2010), where the wire mesh broke at 1800N (Table 2). The shear stress of the epoxy resin was also high, 1202N, but the connection broke and not the wire mesh (Figure 2.14A).

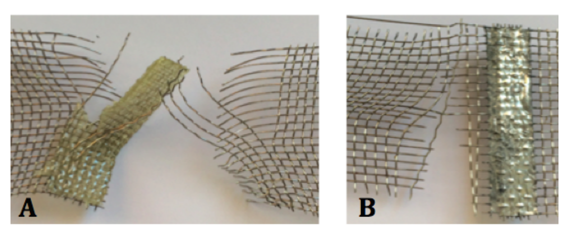


Figure 2.14: *The wire mesh samples after the strength test when connected with 1cm overlapping with the two methods; epoxy resin (A) and soft soldering (B). In the soft soldering sample the wire mesh broke instead of connection.*

Socket

To evaluate the strength of the new socket two different tests were performed. The result of the first test showed that the socket could withstand an axial force of more than 100N without deforming and/or breaking. A total of 10.8kg (108N) was loaded on the socket. In the second strength test when a radial load of more than 6.8kg (68N) was applied to the mesh socket it started to deform (Figure 2.15A). Since the deformation started before 100N was reached, stainless steel wire mesh plates were soldered to the socket to increase the stiffness (Figure 2.15B) and same test was performed again. The result of the third test showed that the socket could withstand a radial force of more than 100N. A total of 12.2kg (122N) was loaded on the socket without deforming and/or breaking (Figure 2.15B).

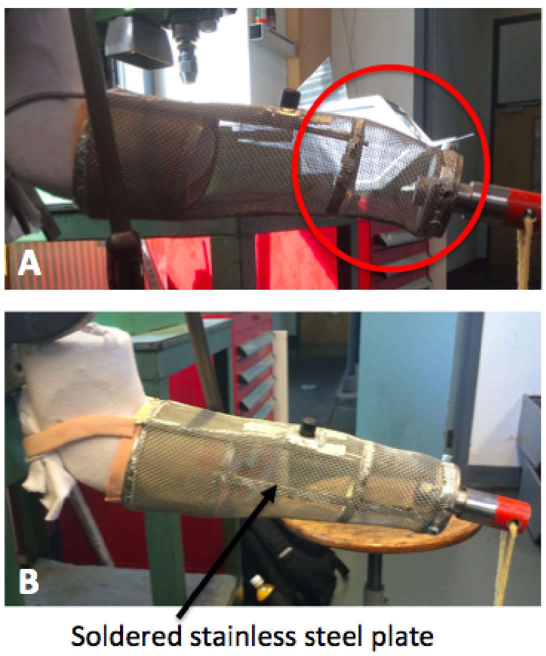


Figure 2.15: The wire mesh socket when radial force is applied to it. A: The distal end of the socket was deformed when it was loaded with more than 6.8kg (test 2). B: Stainless steel plates were soldered to the socket and it did not deform when it was loaded with 12.2kg (test 3).

III.2.2 Prototype

The proposed design for the new WILMER Open Socket can be seen in Figure 2.17. The final socket was made of *stainless steel wire mesh*. The distal and proximal rings were made out of stainless steel plates (Figure 2.17a) and these were connected to a small piece of wire mesh socket deformed around the residual limb. The mesh edges of the small socket were connected with stainless steel *H-profile* using two-component glue (Figure 2.17b). The H-profile was chosen because it had higher strength than the wire mesh, it is made of stainless steel that is biocompatible with the skin (Hermawan et al, 2011), and the mesh edges were easy to connect. The soft soldering connection had also higher strength than the wire mesh (Table 2). But it uses tin alloys as a solder material, which is not biocompatible with the skin (Dikshith, 2008) and the edges were also more difficult to connect. The drawback of the H-profile was the thickness (2mm). Therefore, some parts of the long socket that was not in contact with the skin were connected with soft soldering.

Two V-shaped *guiding tubes* were soldered to the small mesh socket for the guidance of the locking mechanism and the condyle brace (Figure 2.17c,f). The condyle brace had the same design as the original WILMER brace but it was made of a 3mm tube, instead of 5mm. The stainless steel tubes were covered with soft, skin-color foam sheet, which makes it more comfortable to wear and give a life-like appearance (Figure 2.17e,f). To protect against abrasion the foam was covered with polyurethane coating, which is also done in the current open socket.

The long socket, also made of stainless steel wire mesh, was soldered to the small socket and the mesh edges were connected with both soft soldering and H-profile. In the first part of the socket where the small socket and long socket have the same diameter, the two socket's edges were connected to each other with soft soldering. However, when the diameter of the large socket start to deviate from the small socket, the mesh edges of the long socket were connected with an H-profile (Figure 2.18B and D). A small hole was made through the wire mesh for the button (Figure 2.17g), and when the button is pressed the socket can be donned and doffed using one hand (Figure 2.16 and 2.17h).

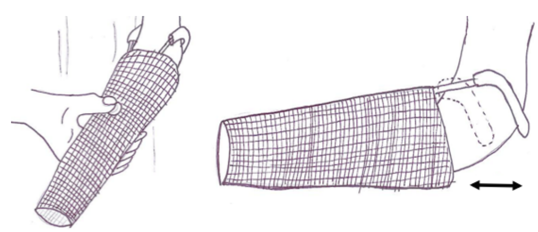
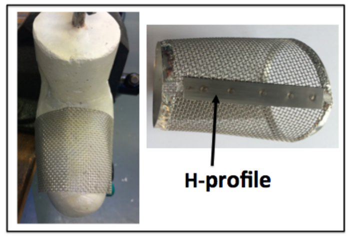


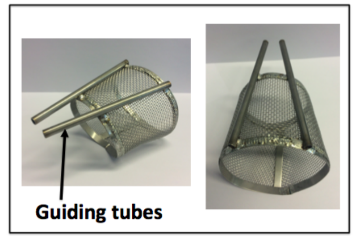
Figure 2.16: When the button is pushed the socket can be adjusted using only one hand (left figure). The right figure shows the condyle braces in open position.

The terminal device was connected to the distal end of the socket with a designed wrist joint (Figure 2.17i). To remove the sharp edges 7 different

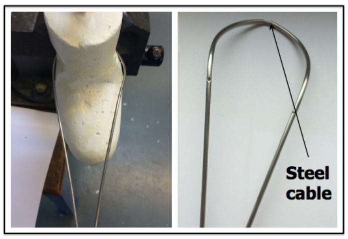
(a) *The proximal and the distal ring, made out of stainless steel plate, is fitted to the residual limb.*



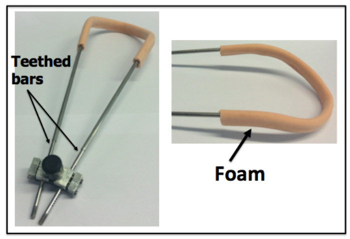
(b) *The wire mesh is deformed around the arm remnant and connected with an H-profile using two component adhesive (epoxy resin).*



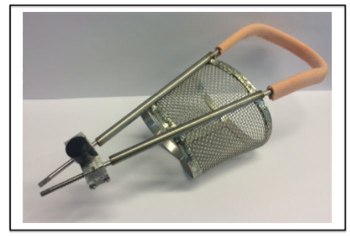
(c) *The V-shaped guiding tubes for the locking mechanism and the brace are soldered to the small wire mesh socket.*



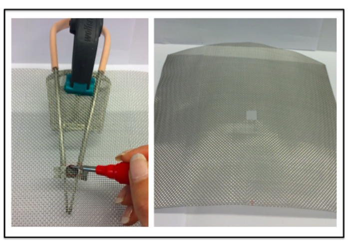
(d) *A 3mm tube is deformed to a condyle brace and fitted around the arm. Then it is cut in half and a small piece of steel cable is soldered inside the braces.*



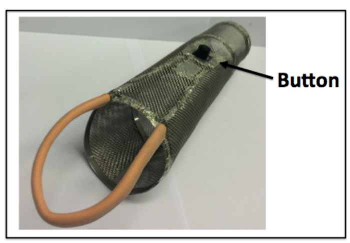
(e) *The two teethed bars from the locking mechanism are soldered inside the brace's tubes and the brace is covered with foam.*



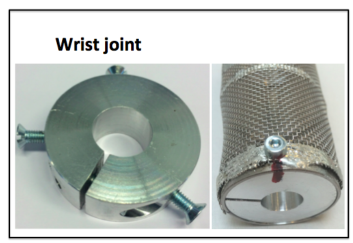
(f) *The locking mechanism and the condyle brace are inserted into the V-shaped guiding tubes.*



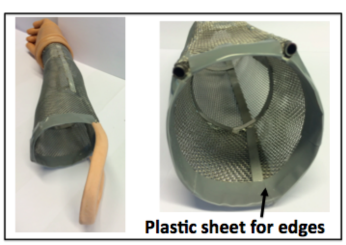
(g) *A piece of wire mesh is cut for the socket and a small hole is made inside the wire mesh sheet for the locking mechanism's button.*



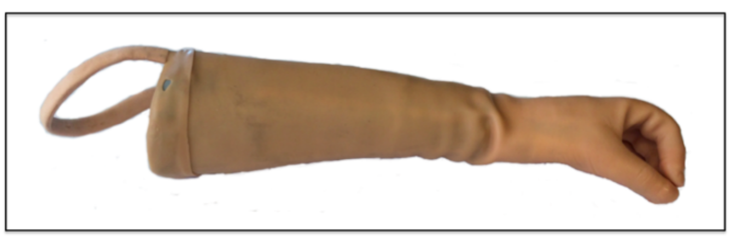
(h) *The stainless steel wire mesh socket is soldered to the small mesh socket from (b) and connected with an H-profile. When the button is pressed the socket can be donned and doffed.*



(i) *The terminal device is connected to the distal end of the socket by using the designed wrist joint.*



(j) *A plastic sheet is glued to the mesh to cover the sharp edges.*



(k) *Final socket: Forearm shell is covering the socket and the terminal device.*

Figure 2.17: *The fitting procedure steps of the new WILMER Open Socket (a more detailed description see Appendix F.II).*

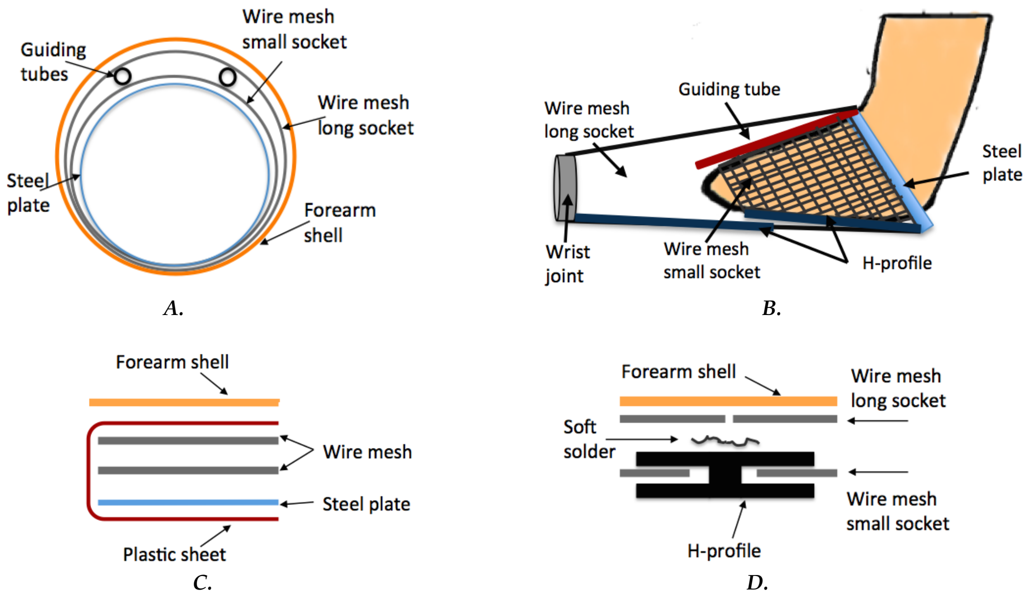


Figure 2.18: *The design of the final WILMER Open Socket: A) Cross section of the socket wall. B) Long and small wire mesh socket connected with an H-profile and soft soldering. C) The different layers of the socket wall at the socket edge. D) The different layers of the socket wall at the wire mesh connection.*

methods were tested and the thickness added to the socket was calculated. The result is summarized in Table 3. In the final socket the sharp edges were covered with a 0.2mm thick plastic sheet, which was glued with two-component adhesive (epoxy resin) to the edges. This method was chosen because it added the lowest thickness to the socket. In the final design, the wire mesh socket and the terminal device were covered with a standard skin-colored forearm shell to give a more aesthetically pleasing look (Figure 2.17k). For a more detailed description of the fitting procedure, see Appendix F.II.

The thickness of the final socket materials can be seen in Table 4 and Figure 2.18 shows the different socket layers. The edge of the socket consists of a steel plate (the proximal ring), two layers of stainless steel wire mesh and plastic sheet, and one layer of forearm shell covering the mesh (Figure 2.18C). The total thickness of the socket was approximately 3.5mm (<5mm) at the socket edge and approximately 7mm (>5mm) at the guiding tubes (Figure 2.18A). The thickness at the wire mesh connection was approximately 3.7mm (<5mm), which consists of the layers; H-profile, wire mesh and forearm shell covering the mesh (Figure 2.18B and D). The condyle brace had a thickness of 4.4mm (<5mm).

The total weight of the WILMER socket was 180g (<200g), which includes the weight of the wire mesh socket, the locking mechanism and the condyle brace (Figure 2.18h).

Table 3: *The different methods used to cover the sharp wire mesh edges and the thickness added to the socket.*

Method	Thickness [mm]
A. Plastic u-profile	1.6
B. Rubber u-profile	3.4
C. Plastic u profile	2.2
D. Foam	2.5
E. Plastic sheet	0.4
F. Folded wire mesh	1.5
G. Plastic tube	4.3

Table 4: *The thickness of the different materials used in the wire mesh socket.*

Material	Thickness [mm]
Wire mesh	0.74
Steel plate	0.5
H-profile	2
Plastic sheet	0.2
Forearm shell	0.9
Guiding tube	4
Condyle braces	4.4

IV. Discussion

This study was divided into two parts; design of the locking mechanism and design of the socket. In the following, the result of these two parts will be discussed separately.

IV.1 Locking mechanism

A new smaller locking mechanism for the WILMER Open Socket has been designed and manufactured, satisfying all criteria. The final prototype consists of 8 different components: housing, sliders, knives, button, teethed bars, pins, springs and support for the springs and pins. The most important requirement for the new design was to reduce the height. The new system has a height of 7.2mm (<7.5mm), which means that a reduction of 6.8mm has been achieved in comparison to the original locking mechanism (Figure 2.12). The total weight of the final prototype was 9g (<35g). The strength of the mechanism was set to 600N and the new system fulfilled this requirement. A total of 30.5kg (305N) was loaded on one lock without breaking. The new mechanism can be operated with one hand. Each spring was loaded with approximately 1N, thus the force needed to unlock the system is 4N. Miyata et al (2007) and Kepur et al (2010) investigated the maximum force of the index finger for young adults and the maximum force was approximately 30N in both studies. Thus, it can be concluded that the force needed to operate the system (4N) by a 14-year-old child is acceptable. The mechanism can be adjusted into one of the 20 different positions with intervals of 1.3mm and it can be V-shaped when heat is applied to the housing (like the original mechanism) (Appendix F.II, step 9). Once the mechanism was attached to the socket, the button was sanded so no parts were sticking out from the socket (Appendix F.II, step 41).

From the result in can be concluded that a successful mechanism has been designed. Like the design by Bos et al (2012), the height is reduced significantly (6.8mm) but the mechanism is also operated with one hand and no parts are sticking out. In the design of Bos et al (2012) a larger reduction in height (9.5mm) was achieved when the height of the button was not taken into account. Anyhow, since the sliding motion was created with a sideways movement of the button with the thumb and index finger, this part has to stick out from the socket (approximately 7mm). The total height of the mechanism is therefore 11.5mm (4.5+7mm) (Figure 2.3). In the new design a push-button was used to create the sliding motion and this was sanded so no parts were sticking out from the socket. Hence, the total height of the new mechanism is 7.2mm (7.2 + 0mm). This means that a larger reduction in height has been achieved compared to the design of Bos et al (2012) and the original mechanism (14+0mm) (Figure 2.12). However, there are still limitations with the new design. The fixation of the mechanism inside the socket was difficult because the supports were made out of aluminium and could not be soldered to the socket. In the socket prototype this problem was solved by soldering two small steel plates to the socket (Appendix F.II step, 25-26). For the final mechanism the supports can be made out of stainless steel and a small piece of steel plate with 90-degree angle can be soldered to the support and the socket for fixation.

The next step for the locking mechanism is to test the mechanism inside a child's socket. Furthermore, an additional strength test needs to be performed on the mechanism to identify the maximum strength of one lock. If the locking mechanism can withstand a load of approximately 840N (84kg), which is the average weight of male adults in the Netherlands (Statistics Netherlands, 2015), then the mechanism will be strong enough to be tested in an adult's socket as well.

IV.2 Socket

A new WILMER Open Socket has been designed, satisfying most of the requirements. The separate components of the design have been tested and a prototype has been built. In the new design the socket part has been extended from the terminal device to the proximal ring. This way the socket would be seen more as a whole instead of separate parts (socket, shell and terminal device). The socket was made of stainless steel wire mesh. The small socket's wire mesh edges were connected with H-profile and the long socket's edges were connected with H-profile and soft soldering. Strength tests were not performed on the H-profile since this has already been done by Ravensbergen (2010). However, more tests are needed on the H-profile before fitting the socket onto a patient. The wire mesh edges were covered with a plastic sheet glued to the mesh edges with epoxy resin. This method was chosen because it added less thickness to the socket (0.4mm). The condyle brace had similar design as

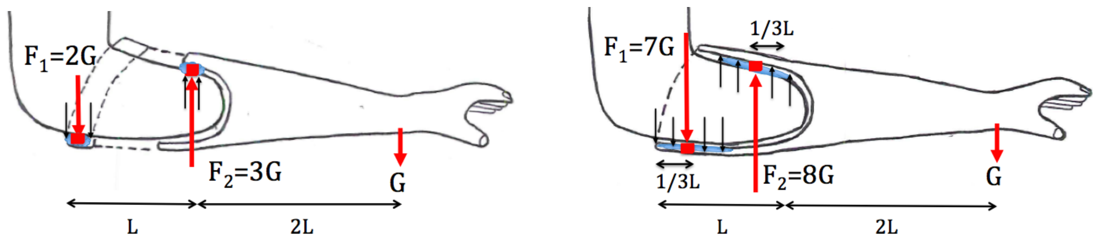


Figure 2.19: *Reaction forces, F_1 and F_2, between the socket and the residual limb. Left figure: Reaction force when a radial force G is applied to the original WILMER Open Socket. Right figure: Reaction forces when a radial force is applied to the new WILMER Open Socket. The pressure is distributed over a larger area.*

the existing socket but it was made out of 3mm stainless steel tube and covered with another type of foam. Inside the brace a small piece of steel cable was inserted instead of a small hinge, like the original socket. For the final design this part (the hinge) needs to be produced for the 3mm tube and additional tests need to be performed on the brace.

The result of the strength test showed that the wire mesh socket is stiff enough to be used by a 14-year-old child. The socket could withstand a radial and axial force of more than 100N before deforming and/or breaking. The result of the second test also showed that by adding small strips of steel plates, the stiffness of the socket could be increased significantly. The second strength test was performed twice. During the first test the socket started to deform when more than 6.8kg was loaded on the socket. But when steel plates were soldered on both sides of the socket (Figure 2.15) the socket could withstand a force of 122N (12.2kg) without deforming. This information can be useful in the future when making the WILMER socket for adults that carry more weight with their prosthetic limb than children. The optimal strength of the socket would be to be able to carry your own body weight, which is 60kg for a 14-year-old child. This was also the design requirement for the socket (see Design criteria II.2). However, this could not be tested in this study but needs to be tested in the future.

For a good fixation of the prosthesis to the residual limb, all forces and moments acting on the prosthesis need to be counteracted (Walta et al, 1989). Figure 2.19 shows the radial reaction forces, F_1 and F_2, between the socket and the limb for the original and the new WILMER Open Socket when a radial force G is applied to the prosthesis. The existing socket has an open structure and the initiated reaction forces will be $2G$ and $3G$ [N] for equilibrium. The new WILMER socket has a complete envelopment of the residual limb resulting in a triangular distributed load between the socket and the limb. The net reaction forces will act approximately one third the width of the triangle. For equilibrium the forces will be $7G$ and $8G$ [N], which is approximately three times larger than the original socket for equilibrium. However, since the new WILMER socket has a complete envelopment of the residual limb, the pressure will be more evenly distributed between the socket and the residual limb, resulting in a lower pressure. The forces and pressure on the skin could not be tested in the final prototype. Anyhow, this can be done in the future with a user research, e.g. by giving the users the task to carry with the prosthetic limb objects with different weights and evaluate the comfort of the socket.

The overall thickness of the socket was approximately 4mm (<5mm), which means that a reduction of about 7mm has been achieved. The thickness was 3.5mm (<5mm) at the edges and 7mm (>5mm) at the guiding tubes. The thickness at the wire mesh connection was approximately 3.7mm (<5mm) and the condyle brace had a thickness of 4.4mm, which is within the design requirement. The condyle brace was covered with foam and by sanding it the thickness of the condyle can be reduced even more. The total weight of the socket was 180g (<200g). Smoother transition between the socket and the limb was achieved everywhere except where the two guiding tubes are located.

There are still limitations with the new WILMER Open Socket. The deformation of the wire mesh to a socket was difficult. This problem can by solved by using a dummy shaped as the human arm to deform the wire mesh. Furthermore, the permeability of the wire mesh has been verified before by Gelderblom (1980) but the permability of the wire mesh covered with forearm shell has not been tested yet and can be done with user research.

The next step for the WILMER socket is to fit the socket onto a child's limb and test and evaluate the prosthesis. Important aspects to evaluate are: the comfort of the wire mesh socket, the donning and doffing, the permeability and the patient's opinion on the design. Moreover, the fitting procedure needs to be evaluated in a standard prosthetic facility and some of the steps need to be simplified.

V. Conclusion

A new WILMER Open Socket that fits closer to the skin and is more aesthetically pleasing has been designed of stainless steel wire mesh. Furthermore, a new design was also made for the locking mechanism and from the result, it can be concluded that a successful mechanism has been designed that reduces the thickness of the socket for children and patients with long and thick residual limbs. The obtained results of the socket and the mechanism are summarized as follows.

- The reduction of the socket's overall thickness to 4*mm* (original 11*mm*) creates a smoother transition between the socket and the residual limb.
- A forearm shell covering the wire mesh gives a more natural looking prosthesis.
- The mechanism has a height of 7.2*mm*, which is almost half the height of original mechanism (14*mm*).
- Like the existing WILMER socket the new design is adjustable and it can easily be donned and doffed.

The new WILMER Open Socket can have a great value for below elbow amputees since improvement of the cosmetic value of the prosthesis can result in increased wearing.

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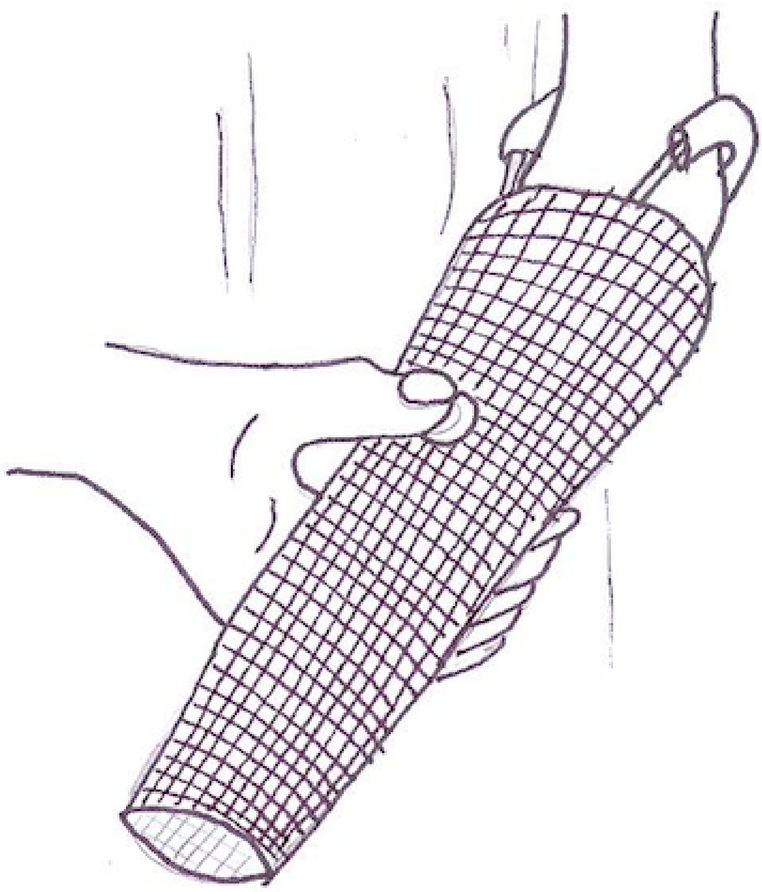
Appendix



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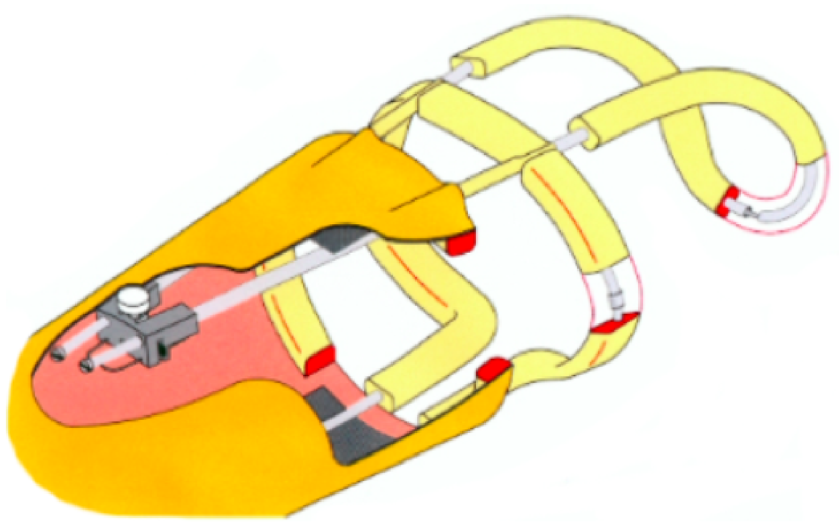
Appendix A

WILMER Open Socket



I. Locking mechanism

The original locking mechanism consists of six different components; housing, two teethed bars, knife, button, spring and two bolts (Figure A.1). The first component is the housing where all other components are inserted. The second component is two teethed bars where the knife goes in and locking the system. The fourth component is the button, which is inserted on the top of the housing. A spring is attached on the other side of the housing and when the button is pressed, the system is unlocked and the braces can be adjusted into one of the 20 different positions with intervals of 1.3mm. At the end of each bar a bolt is attached so the condyle braces do not go out from the housing during donning and doffing (Figure A.3).

The current WILMER locking mechanism has a height of 14mm (Figure A.2). This height is the mechanism's biggest issue and causes a thicker socket for children and patients with long and thick residual limbs (see Chapter 1, Introduction). The weight of the locking mechanism for a child version is approximately 35g and for an adult 50g.

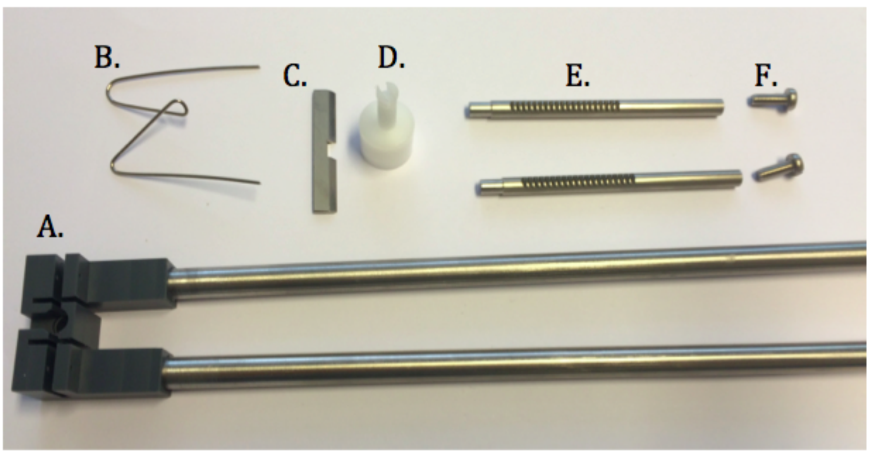


Figure A.1: *The different parts of the original locking mechanism: A) Housing B) Spring C) Knife D) Button E) Teethed bars F) Bolts.*

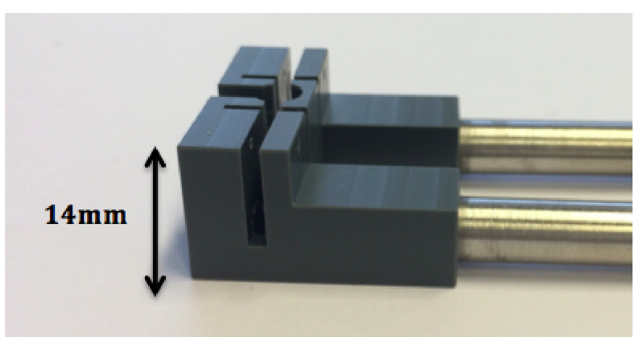
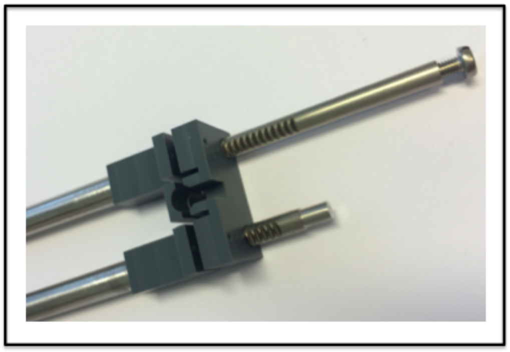
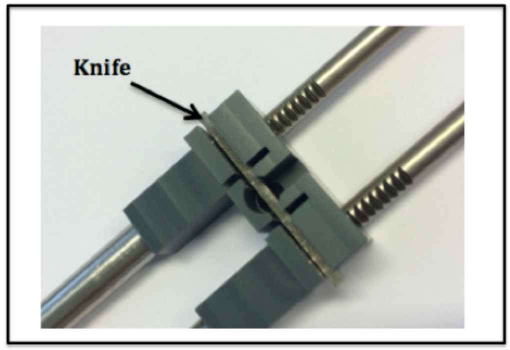


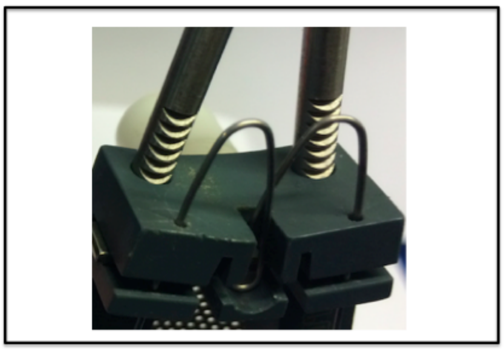
Figure A.2: *The height of the current mechanism.*



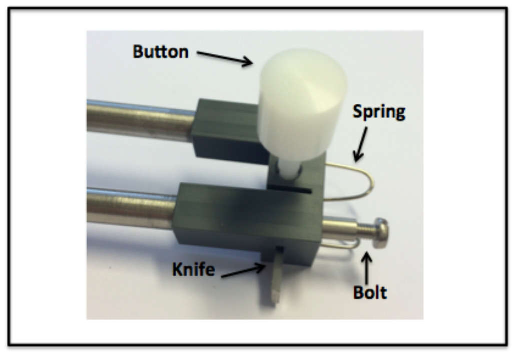
(a) *The teethed bars and the bolt.*



(b) *The knife and the two teethed bars.*



(c) *The spring.*



(d) *The button, knife, spring and the bolt.*

Figure A.3: *The original locking mechanism.*

II. Fitting procedure

The WILMER Open Socket is fitted directly onto the patient, which reduced the number of steps needed to produce a ready-to-wear socket for the patient [7]. The socket is produced in two stages. In the first stage the supplier, *Delft Prosthetics*, gathers and makes all the materials and parts needed to make the socket. The locking mechanism is fabricated, the stainless steel tubes are cut in the correct sizes and the foam has to be cut and holes are made for the tubs [6]. Figure A.4 shows all the materials and parts the supplier needs to send to the clinics that produces the socket (stage 2). Below is the fitting procedure made by the clinicians in Sint Maartensklinik, Nijmegen, the Netherlands, to produce current WILMER Open Socket described step-by-step [10]. Some of the steps in the fitting procedure have recently been changed. Earlier, the suppliers send long tubes and the clinicians had to make the proximal rings and the braces. Currently the supplier, *Delft prosthetics*, makes the condyle braces and the proximal rings (Figure A.5) and send it to the clinics for fabrication. Thus, the steps 2-5 and step 13 are no longer done in the fitting procedure.

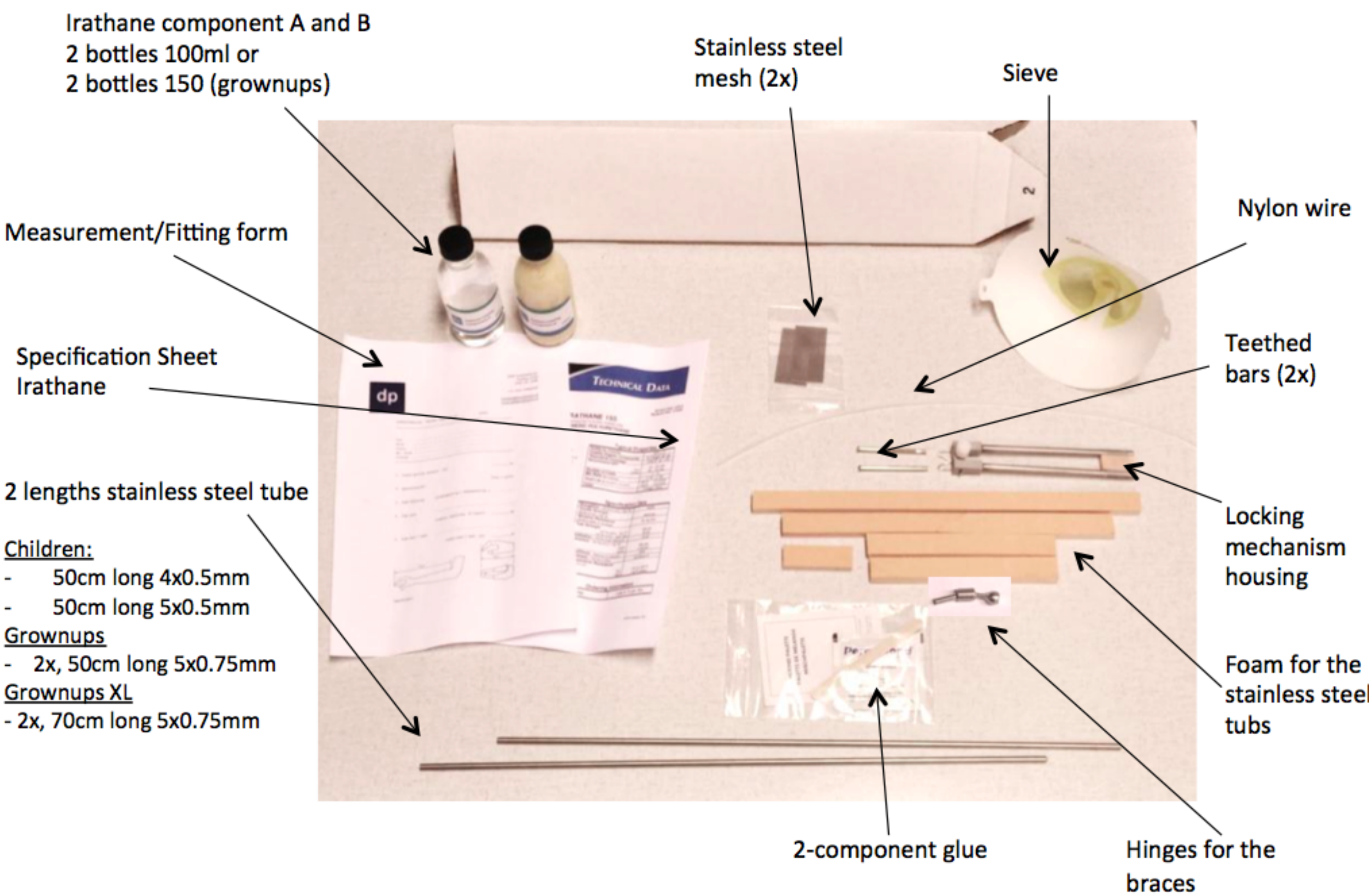
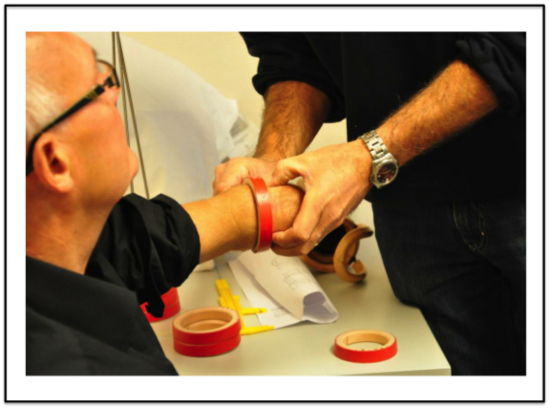
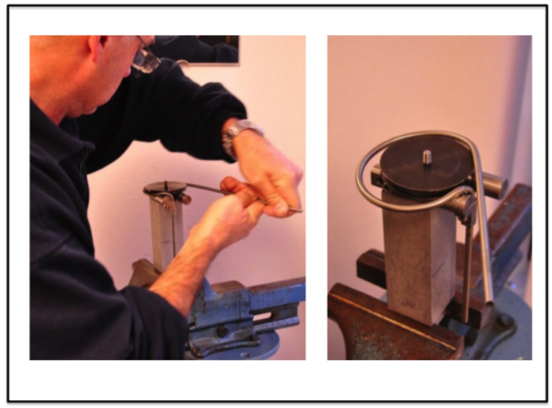


Figure A.4: *Material and parts needed to fabricate the current WILMER Open Socket [10].*

Fitting procedure of the original WILMER Open Socket

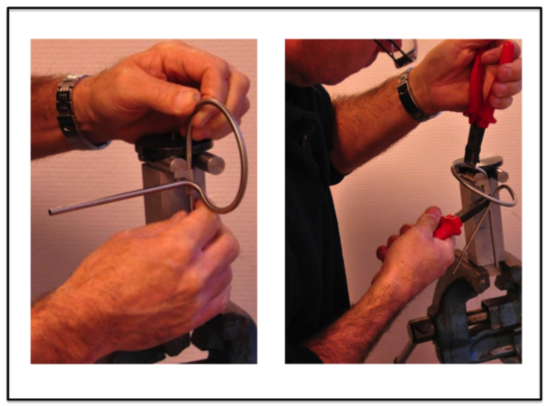


1. Fit the proximal ring to the residual limb.



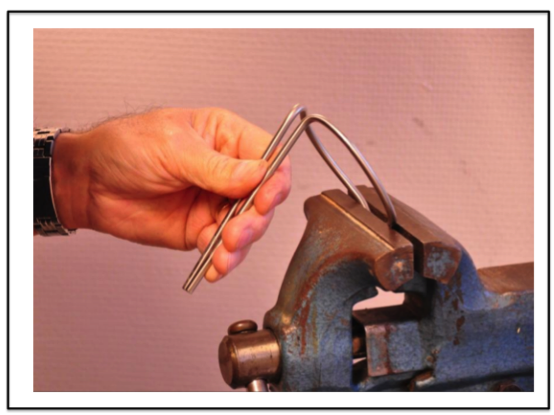
2. Bend the stainless steel tube to a proximal ring.

3. Compare to the fitting-ring.



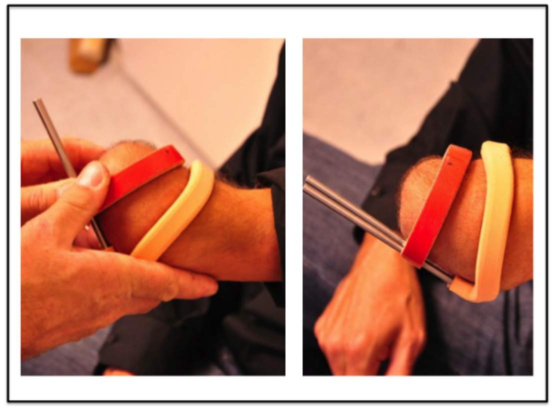
4. Bend the second proximal ring.

5. Fit the proximal ring to the residual limb.

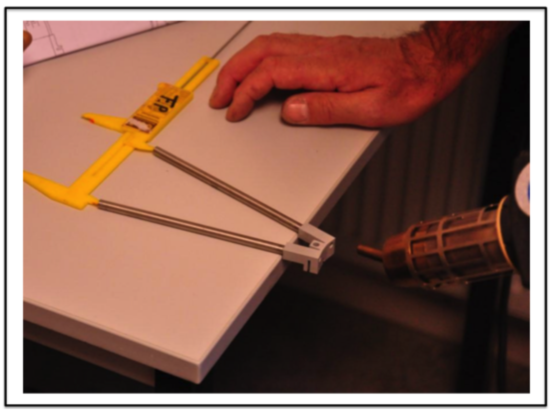


6. Bend the middle-part of the proximal ring.

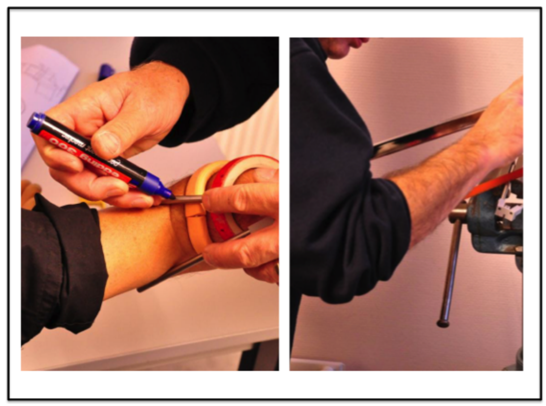
7. Cover the proximal ring with foam and fit it around the limb.



8. Fit the distal fitting-ring into the proximal ring's tubes.



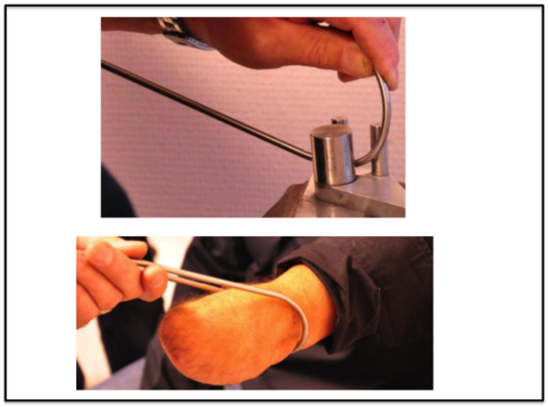
9. Heat the housing of the locking mechanism and bend it into a V-shape.



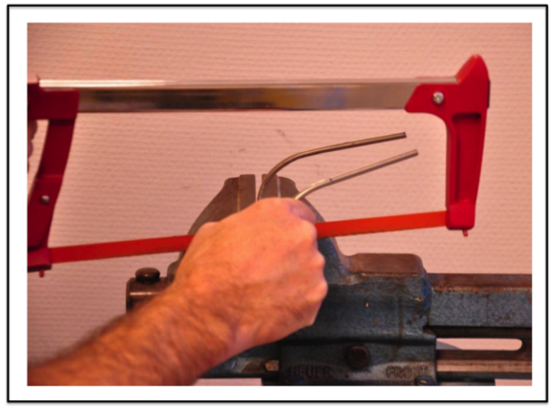
10. Mark the end of the guiding tubes and saw off the rest.

11. Monitor the test-socket-holder and fix it with adhesive tape.

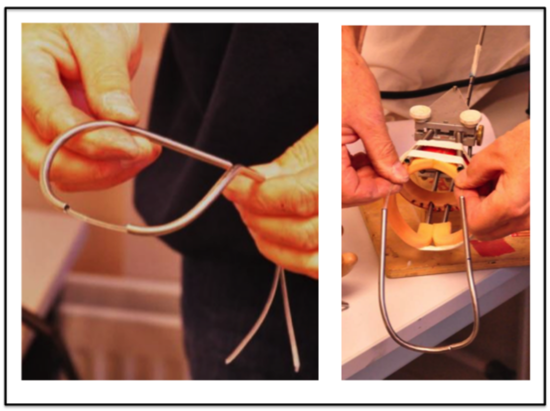
12. Draw the condyle brace position.



13. Bend the condyle brace and fit it around the arm remnant.

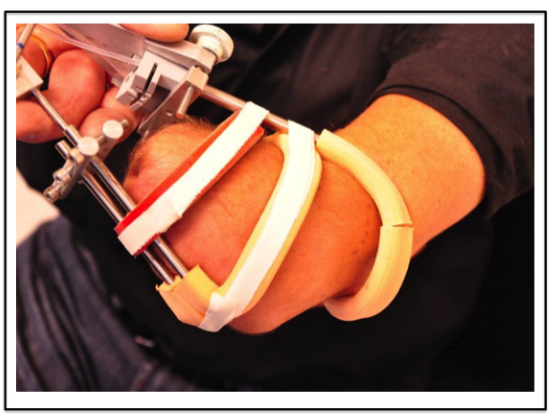


14. Saw in the middle of the condyle brace.

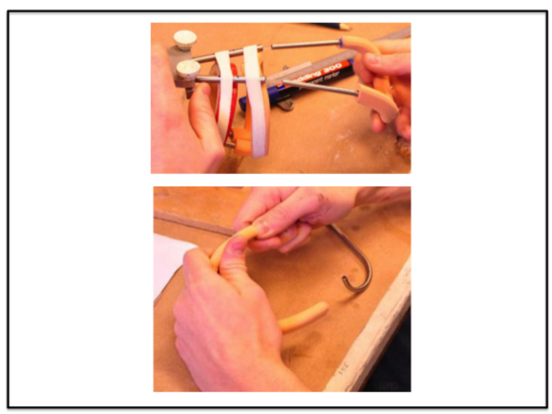


15. Insert a nylon wire into the brace's tubes, and connect it to the socket.

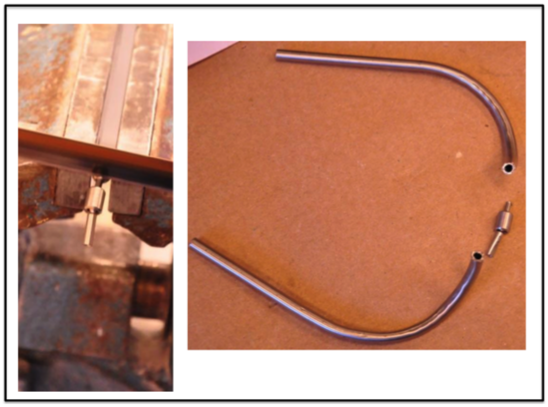
16. Tape the sawed end.



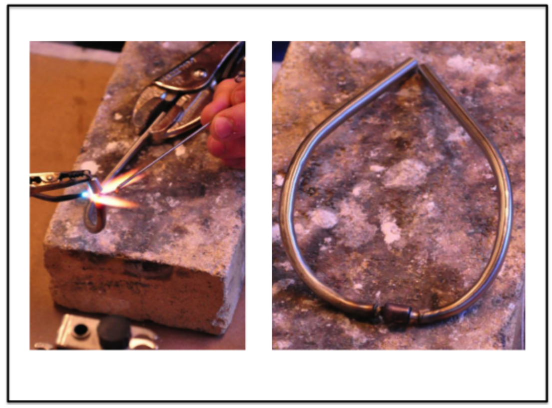
17. Put foam around the braces and fit the socket to the limb.



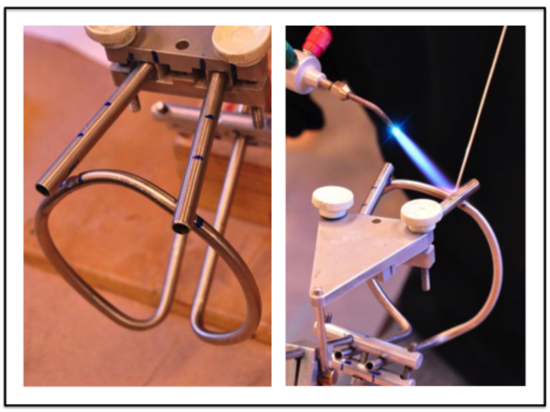
18. Remove the condyle brace from the socket and the foam.



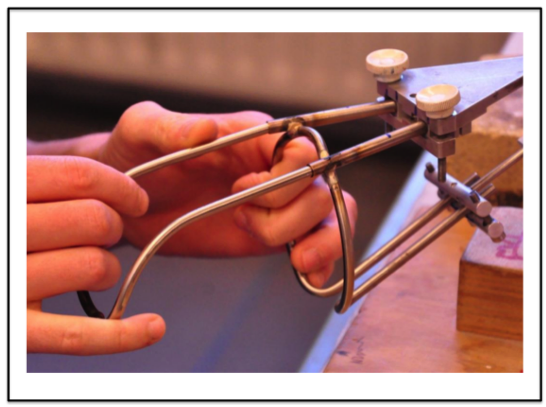
19. Saw off the ball-hinge piece so it fits into the condyle brace.



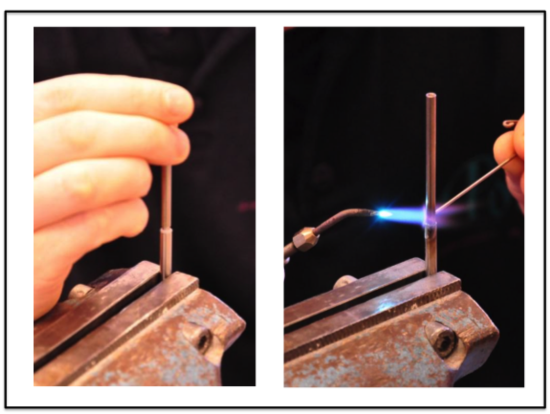
20. Solder the hinge to the condyle brace.



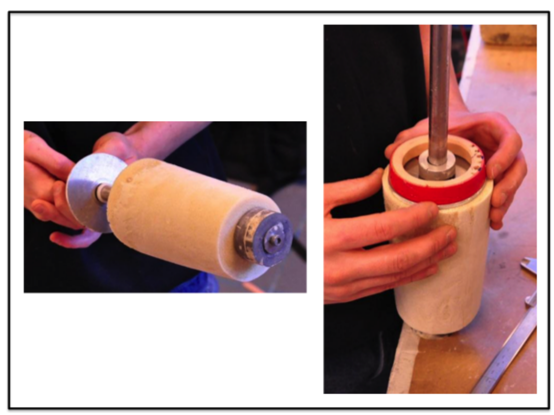
21. Mark the position of the guiding tubes and solder it to the proximal ring.



22. Fit the condyle brace into the guiding tubes.

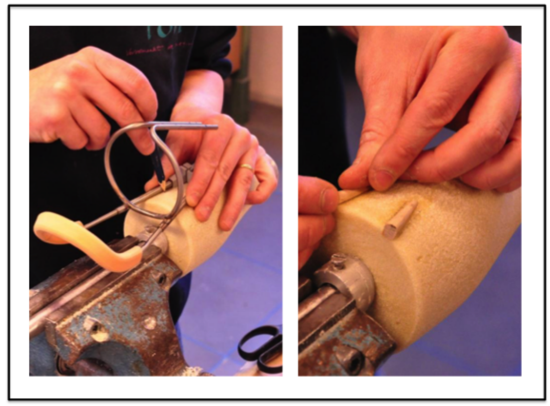


23. Insert the teethed bars into the condyle brace and solder it.



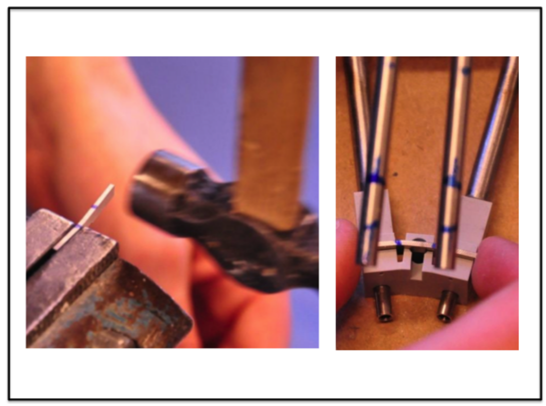
24. Use a dummy to make the socket. Control the diameter of the dummy with the fitting-ring.

25. Customize the dummy so it fits to the patient's residual limb.

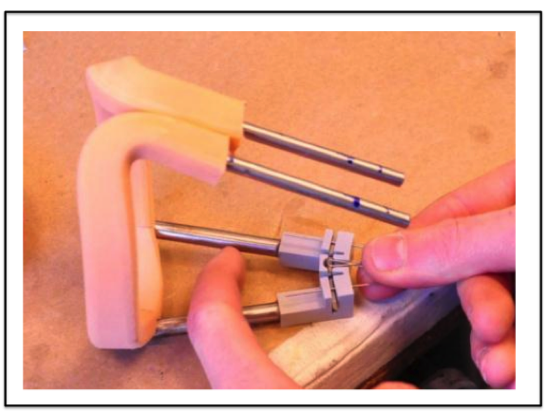


26. Mark the position of the guiding tubes and put an insert for the tubes.

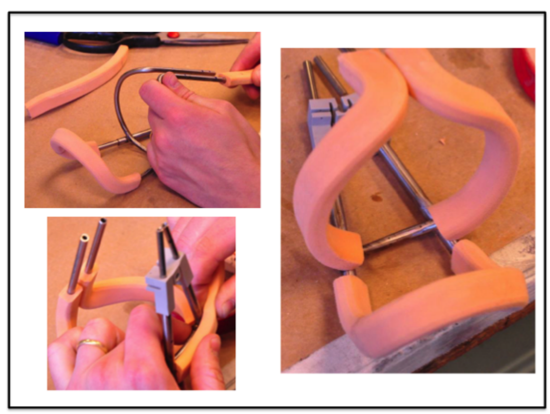
27. Fabrication of the socket.



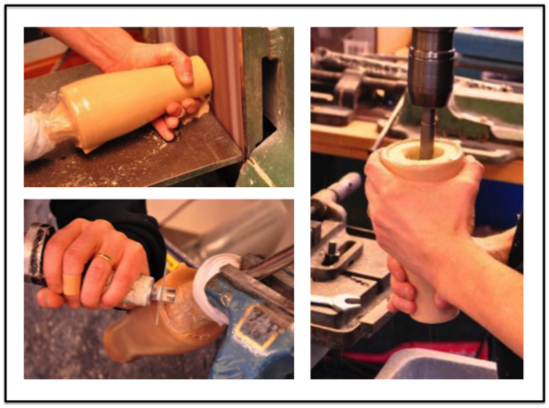
28. Bend the knife and insert it into the housing of the locking mechanism.



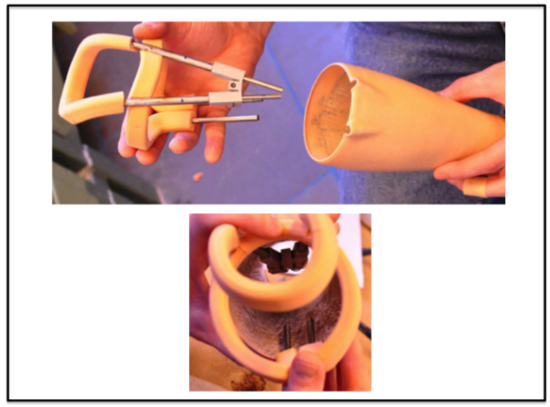
29. Insert the springs into the locking mechanism.



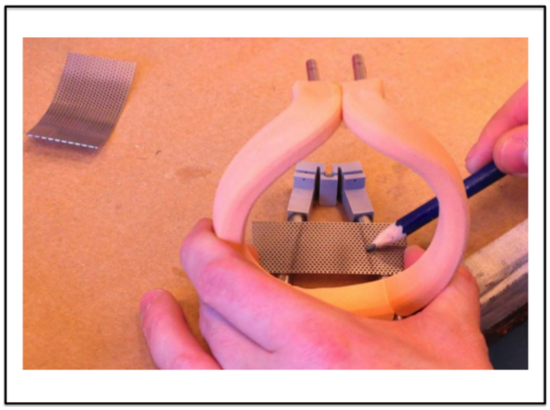
30. Put foam around the tubes.



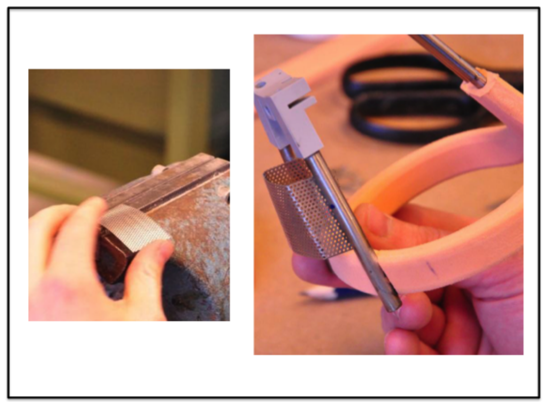
31. Remove the foam so only the socket is left.



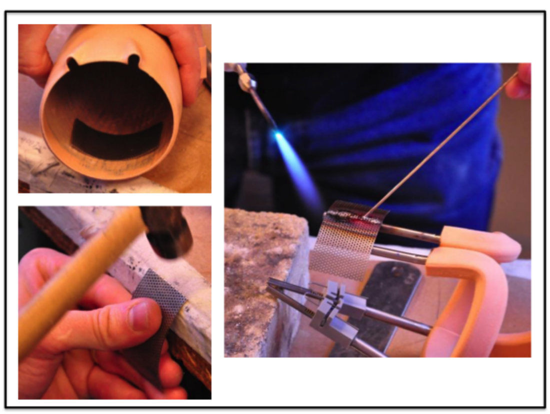
32. Fit the WILMER prothesis into the socket.



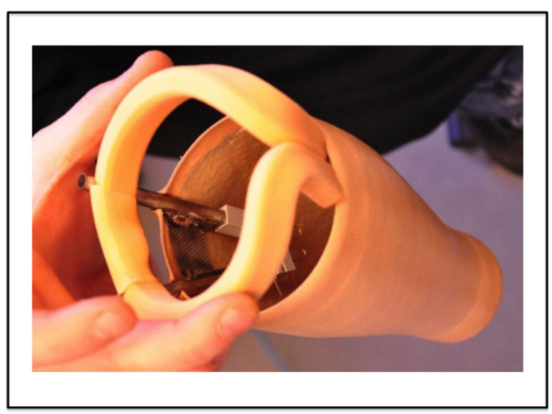
33. Use the stainless steel mesh and mark the guiding tubes position.



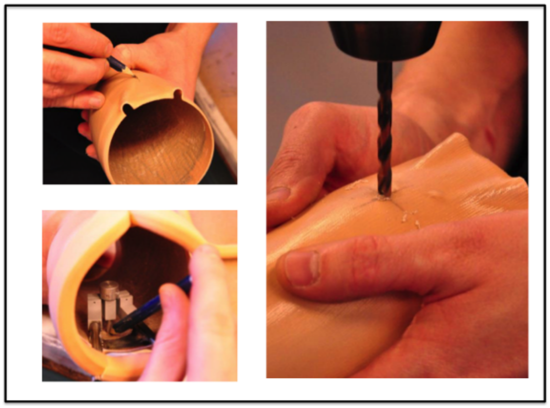
34. Bend the stainless steel mesh plate and solder it to the guiding tubes.



35. Fit the bottom stainless steel mesh to the socket and solder it to the WILMER Open Socket.



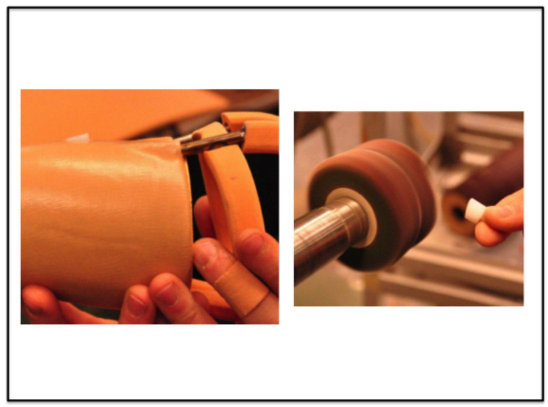
36. Fit the stainless steel mesh into the socket.



37. Mark the position of the button and drill a hole.

38. The push-button inside the socket.

39. Apply carbon fiber material and fixate it with glue.



40. Determine how much the button is sticking out and sand it.

41. Sand the socket.

42. Check it and later coat the foam with irathane to protect against abrasion.

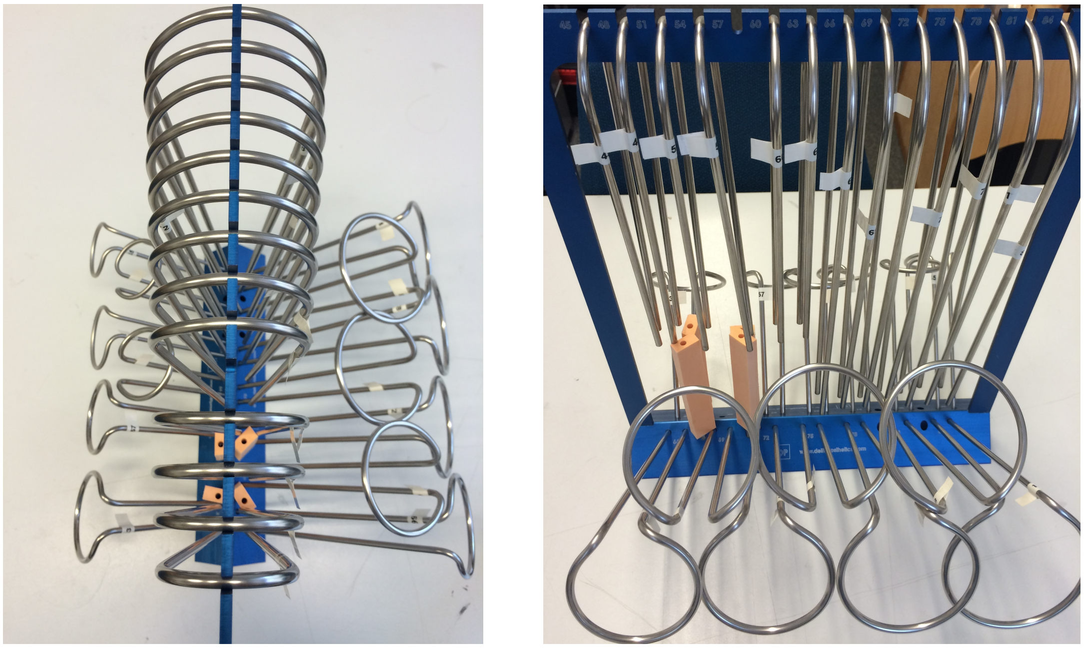
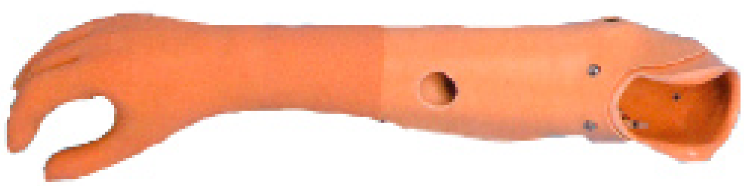


Figure A.5: *The condyle braces and the proximal rings made by the supplier Delft Prosthetics.*

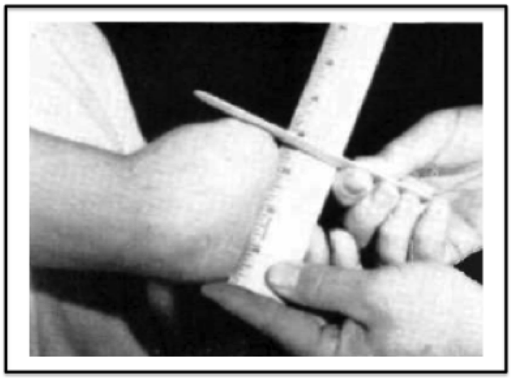
Appendix B

Münster socket

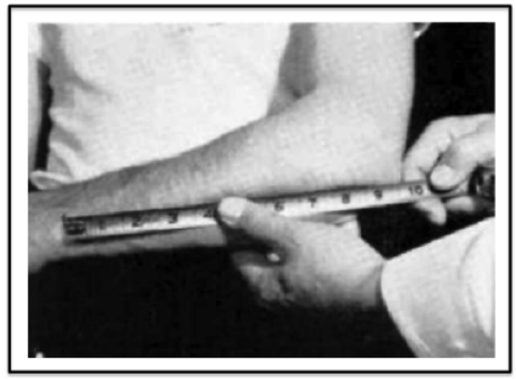


I. Fitting procedure

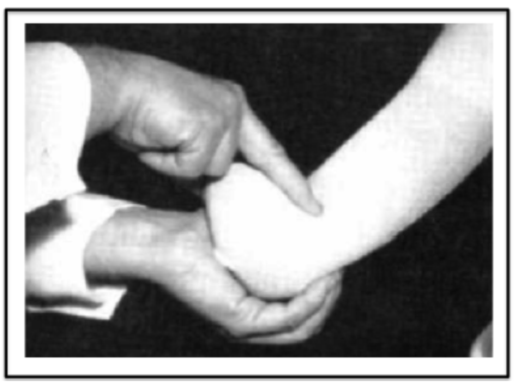
In this section is the fitting procedure of the Münster socket described step-by-step [5].



1. Measure the stump length.

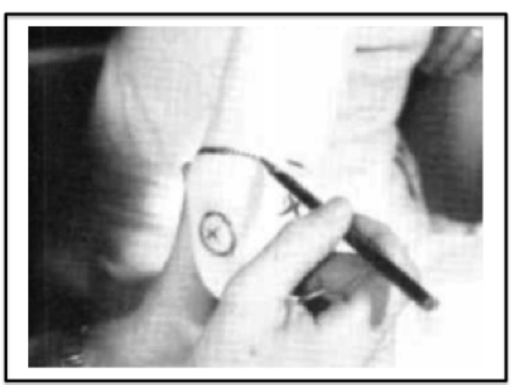


2. Measure the forearm length.



3. Practice the molding grip by position the left hand against the underside of the stump.

4. Mark tender areas and bony prominences e.g. olecranon, epicondyles and the end of the stump.



5. Mark the proximal trim line.

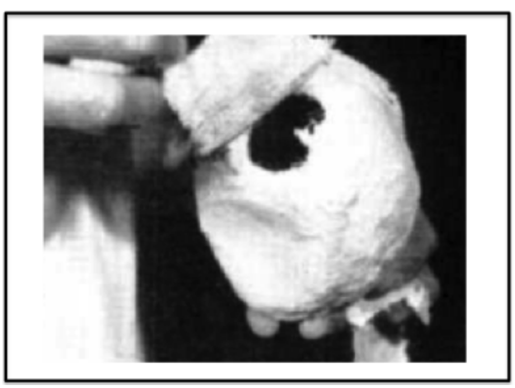
6. Wrap the stump with a bandage.

7. Apply molding grip to the wrap cast and shape it.

8. Remove the wrap cast when it hardens.

9. Pull the stump into the check socket and determine the adequacy of the fit.

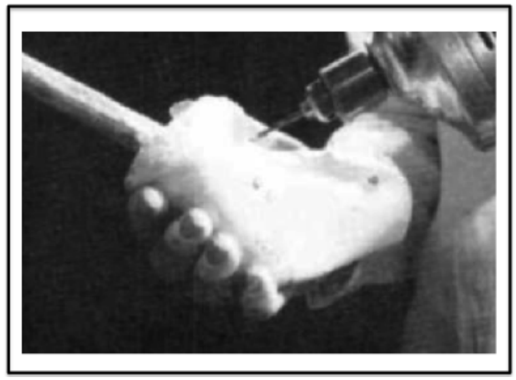
10. Mark the areas that require relief.



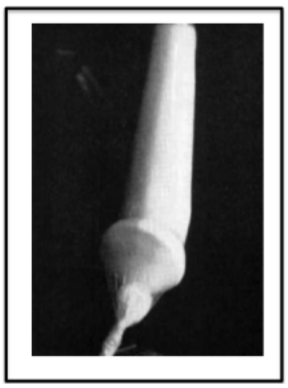
11. Close the distal end of check socket with a bandage or a tape.

12. Fill the check socket with liquid plaster of Paris and insert a hollow pipe into the plaster.

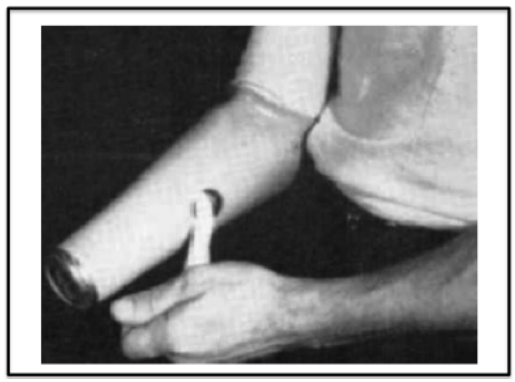
13. Build the distal end of the model to increase the length of the socket.



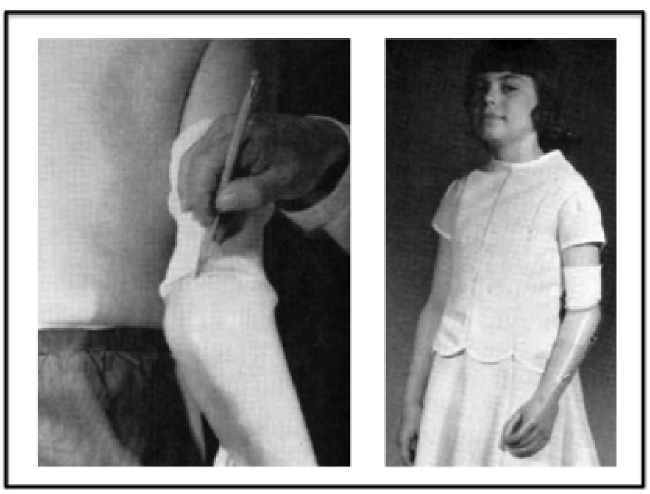
14. Drill holes through undercut areas at the proximal end of the positive model to be able to draw the PVA bag during vacuum lamination.



15. Forearm extension over the socket.



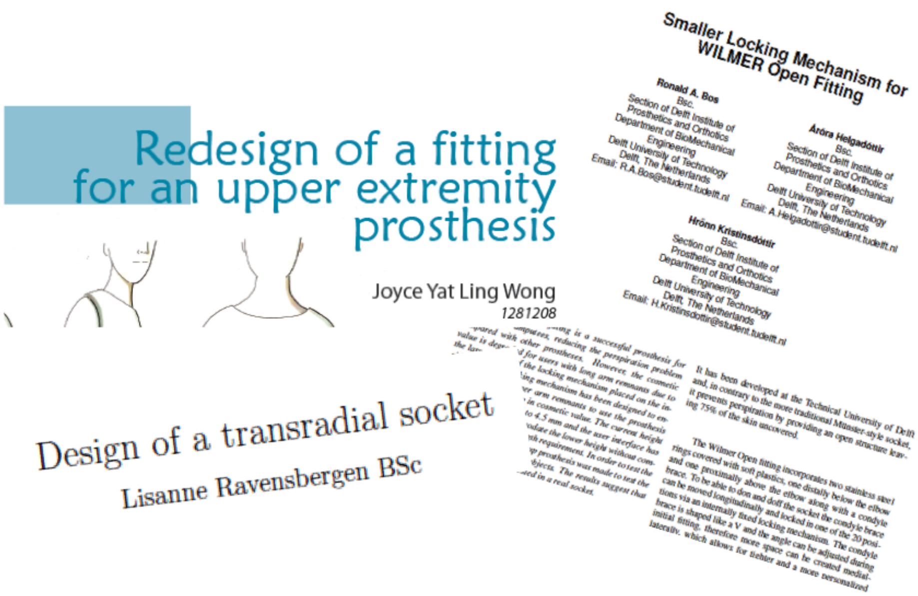
16. Drill hole through the forearm shell wall to permit passage of the stump pulling sock.



17. Check the fitting on the patient.

Appendix C

Previous studies



PREVIOUS STUDIES

In two previous Master Thesis done by Wong, (2008) and Revensbergen, (2010) at Delft University of Technology (TU Delft), the WILMER Open Socket was redesigned to improve the cosmetic value. In another previous study done by Bos et al (2012) at TU Delft, a smaller locking mechanism was designed for the WILMER socket [11]. In this section a short summary of all three theses studies will be presented.

I. Wong (2008)

In the study of Wong (2008), a new design for the WILMER Open Socket was proposed, which can be seen in Figure C.1. The socket and the two braces were made of stainless steel metal foam. In her design the upper part of the socket was extended to the proximal ring and the distal ring was replaced with the metal foam socket. This way the socket would be seen more as a whole design. The proximal ring was removed and two braces were used instead, which were attached to the metal foam. The first brace goes under the arm, below the elbow, and the second brace goes above the elbow. In her study a real prototype was not built [8].

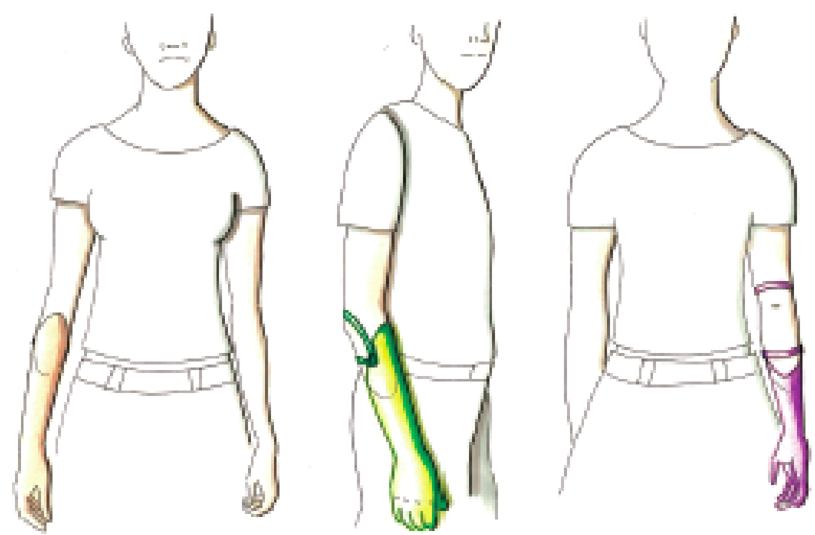
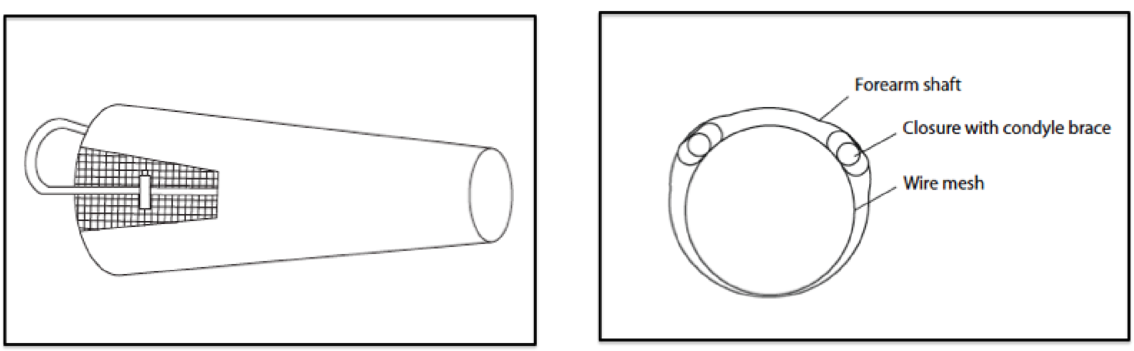


Figure C.1: *The WILMER Open Socket designed by Wong. Front, side and back view [8].*

II. Ravensbergen (2010)

Ravensbergen (2010) did a material research on different materials applicable in the prosthetics field. The different material-groups she looked at were textiles, foams and metals such as hybrix, wire mesh and metal foams (from Wong's study). The material that fulfilled her design requirements the most was stainless steel wire mesh, thus this material was chosen for the final socket. The socket material stainless steel metal foam, which was proposed by Wong (2008), was rejected by Ravensbergen (2010) due to the high price (approximately €215 per socket) [6].

The final design of Ravensbergen (2010) can be seen in Figure C.2 and C.3. The socket was made of stainless steel wire mesh. To connect the mesh edges an H-profile of polyurethane was selected for the final prototype but strength test could only be performed on the wire mesh glued in an aluminium H-profile. The result showed that when enough adhesive was used (all wire mesh holes was filled with the glue) at a maximum tensile strength of 1.8kN the mesh was broken instead of the glue (Figure C.5). To cover the mesh a forearm shell was used, which was connected to the wire mesh socket with glue and polyurethane U-profile. The proximal and distal rings of the original WILMER socket was replaced by the stainless steel wire mesh socket. The condyle braces were connected with ball-joint like the current socket. The braces were cushioned with space fabric covered with evalon and the cushion was attached to the condyle braces with Velcro (Figure C.4). Due to time constraints a real prototype was not built. Furthermore, the design requirement *smooth transition between the arm and the socket <5mm* was not met. The maximum thickness of the socket was 5.5mm, which was at the rim of the socket. Figure C.6 shows some kind of prototype where the stainless steel wire mesh was bent into conical shape and the edges are connected with an H-profile.



(a) *Overview of the socket.* **(b)** *Cross-section of the socket wall.*

Figure C.2: *The WILMER Open Socket designed by Ravensbergen [6].*

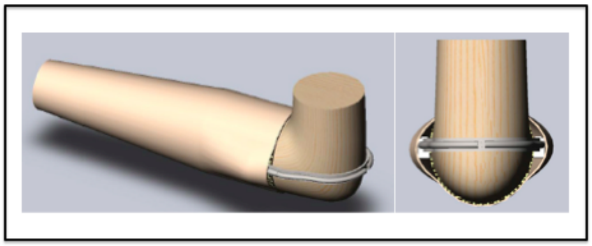


Figure C.3: *Overview of the socket with the locking mechanism and the cushion [6].*

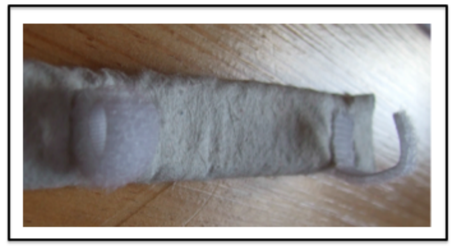
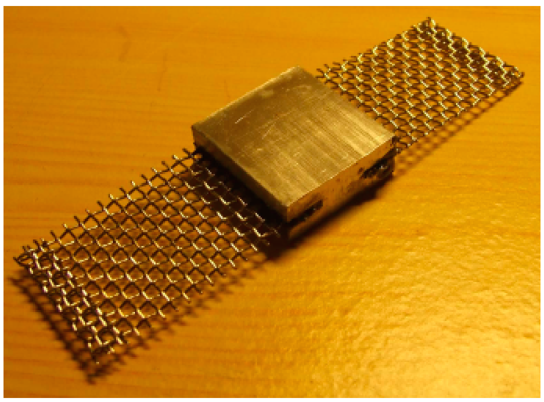


Figure C.4: *The cushioning of the condyle tube with Velcro [6].*



(a) *Wire mesh in an aluminium H-profile when sufficient adhesive was used.*

(b) *Aluminium H-profile, mesh is broken instead of the glue.*

Figure C.5: *H-profile [6] .*

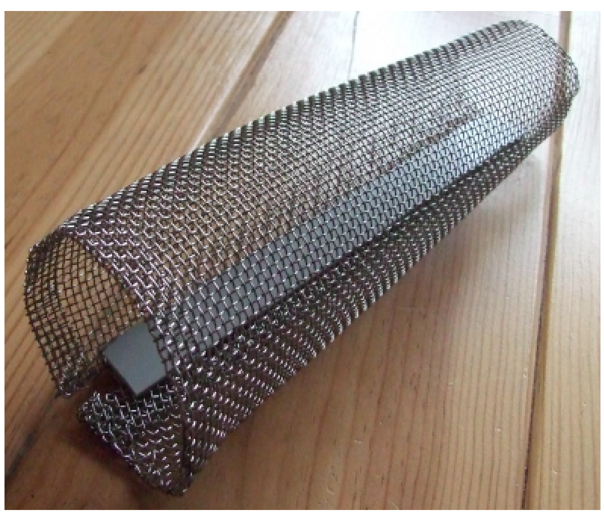


Figure C.6: *Final prototype: wire mesh bent in conical shape and connected with an H-profile [6].*

III. Bos et al (2012)

In a previous study done by three students at TU Delft, a smaller locking mechanism was designed for WILMER Open Socket. Their final design used a sideways movement of the button to release the knife from the locked position and the condyle braces could be adjusted. They used the same working principle as the original locking mechanism, i.e. a knife and teethed bar. Two separate systems were used and not one whole system as the original locking mechanism (Figure C.7). The teeth of the bars were kept to the original height (0.8 mm) but the diameter was reduced to 2.5 mm instead of 3.9 mm (the original bar diameter). According to their force calculation the bar with the new diameter did not break when a maximum force of 250 N was applied to one lock. Figure C.7 shows their 3D model and prototype of the locking mechanism [11].

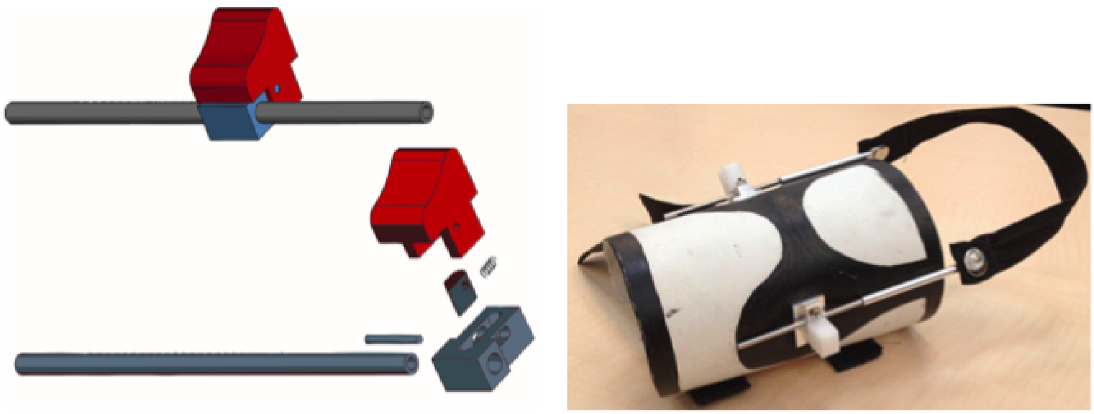


Figure C.7: *The locking mechanism designed by Bos et al (2012) [11].*

With their new design they reduced the height of the mechanism to 4.5 mm instead of 14 mm (original design). Their wish was to have a height lower than 7.5 mm. This limit was chosen based on a comparison between the thickness of a healthy arm and an amputated arm for 13 and 14 year old children. They also reduced the weight to a total weight of 9 g. The weight limit was set to < 37 g, which is less than 5% of the weight of a normal forearm. The bar strength limit was set to > 500 N ($2 \cdot 250$ N). Their argument was that the bar should be strong enough to withstand body weight. Since the average weight of a 12-13 year old child is 50 kg, the force limit was chosen to 500 N [11].

Appendix D

Design criteria

I. Locking mechanism

Easy to operate: The locking mechanism should be easy to lock and unlock, and this should be possible with only one hand. It should not require high force to operate the system.

No parts should stick out: No parts should stick out from the prosthesis, because it does not look natural and it can damage the clothes.

Possible to V-shape: The locking mechanism should be possible to V-shape. The V-shape of the locking mechanism created more space in the medial-lateral direction thus allows easier donning and doffing of the socket and better fit around the limb (see Chapter 1, Introduction I)

Height less than 7.5mm: The current WILMER locking mechanism has a height of 14mm. This height is the mechanism's biggest issue and causes thicker socket (see Chapter 1, Introduction II). In the design of Bos et al (2012) the height of the locking mechanism was limited to less than 7.5mm (see Appendix C.III). The maximum height of the mechanism was calculated by taking the difference between in the thickness of the residual limb and a healthy forearm. Since the arm remnant has less soft tissue than a healthy arm, measurements of the wrist were used to estimate the thickness of the residual limb [11]. Same calculation was also used in this study to estimate the maximum height of the locking mechanism. The anthropometric data was from 13-14 years old healthy children [13, 14]. Because the WILMER Open Socket was originally designed for children it was assumed that the users are children up to 14 years old. The maximum height of the locking mechanism was set to less than 7.5mm.

Calculation of the locking mechanism's height
The mean wrist circumferences for a 14 year old child was approximately 162mm [12] and the mean forearm circumferences was approximately 245mm [13]. Since the locking mechanism is placed on the top of the socket the difference between the forearm and the wrist was calculated in radius, i.e. half of the arm was only considered, which was 13mm (Figure D.1). At the point where the locking mechanism is located (1/3 of the forearm length) the difference in thickness is approximately 8.7mm. However, we do not want the locking mechanism to come in contact with the skin and therefore the maximum height of the locking mechanism is set to less than 7.5mm.

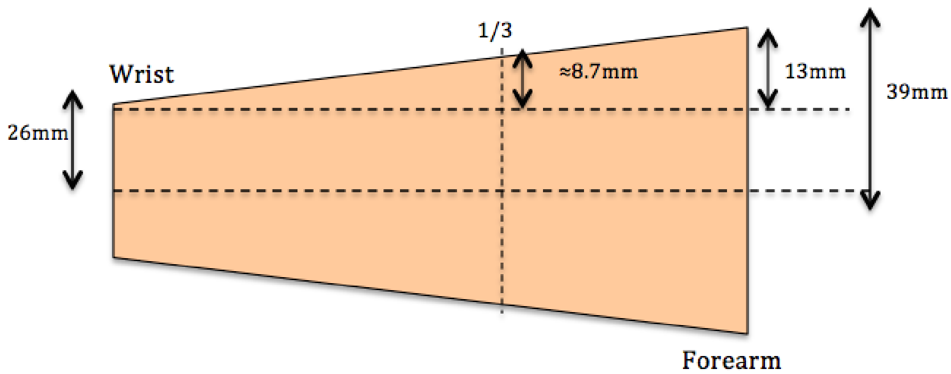


Figure D.1: *Calculation of the maximum height of the locking mechanism.*

Strength higher than 600N: The locking mechanism should be strong enough to withstand the body weight of the user. The average weight for children at age 14 years old is 60kg [14]. Thus, the locking mechanism should be able to withstand a force of approximately 600N.

Weight less than current locking mechanism (<35g): The weight of the new design should be less than the original mechanism for children, which is approximately 35g. Even though the weight of the existing mechanism is not an issue, a light weight socket is always desirable to reduce skin pressure and allow natural handling of the prothesis [7]. Thus, the requirement was set to *less than current mechanism (<35g)*.

The locking mechanism should also be ***waterproof***, i.e. function in the water, ***resistant to corrosion*** and ***stain proof***. The cost is not an important factor, but still it is important to keep the cost minimized.

II. Socket

Smooth transition between the socket and the limb (<5mm): The original WILMER Open Socket has big and bulky braces, and there is a large difference in height between the arm and the socket. The sockets braces covered with foam are approximately 10-12mm thick. Since this is one of the main issues with current socket, this problem is important to solve. The design requirement for the new socket was to have a transition between the socket and the limb less than half the difference of current socket, i.e. less than 5mm.

Adjustable: Since children grow constantly it is desirable to have the socket adjustable. This is one of the advantages with current WILMER socket and it should also be kept in the new design. With the locking mechanism the braces should be adjusted into one of the 20 different positions with intervals of 1.3mm.

Easy donning and doffing: The new socket should easily be donned and doffed. This is also another advantage with current socket and should be kept in the new design. With the locking mechanism the patient should be able to easily don and doff the prosthesis using one hand.

Self-suspension: The patient should be able to self attach the prosthesis to the arm with one hand.

Sufficient ventilation of the socket: The current WILMER socket uses the minimal area for fixation of the socket and leaves 75% of the skin uncovered to minimize the perspiration problems (see Chapter 1, Introduction I) [2]. To keep this advantage the new design should either leave 75% of the skin uncovered or be made of breathable material. However, Wong (2008) found in a user research study of WILMER socket that many users still complain about perspiration and heat problems [8]. Therefore, it was decided to make the new socket of breathable material to minimize the heat and perspiration problems.

Lightweight: The new socket should be lightweight to reduce skin pressure and create natural handling of the socket [7]. A child's version of the WILMER socket weighs approximately 200g [8]. The goal with the new design was to keep the weight equal or less than the current socket .

Strength higher than 600N: The socket should be strong enough to withstand the body weight of the user. The average weight for children at age 14 years is 60kg. Hence, the socket should be able to withstand a force of 600N.

Comfortable material: The socket should be made out of comfortable material. The material should be biocompatible with the skin and easy to clean.

Lifelike: The socket should have lifelike appearance. It should have skin color, covered with soft material, no parts should stick out and there should be no sharp edges.

Waterproof: The socket and all the parts of the socket should be waterproof. The patient should be able to use the socket in the water.

Easy fitting procedure: The socket should be possible to fit in a standard prosthetic facility (see Appendix A.II).

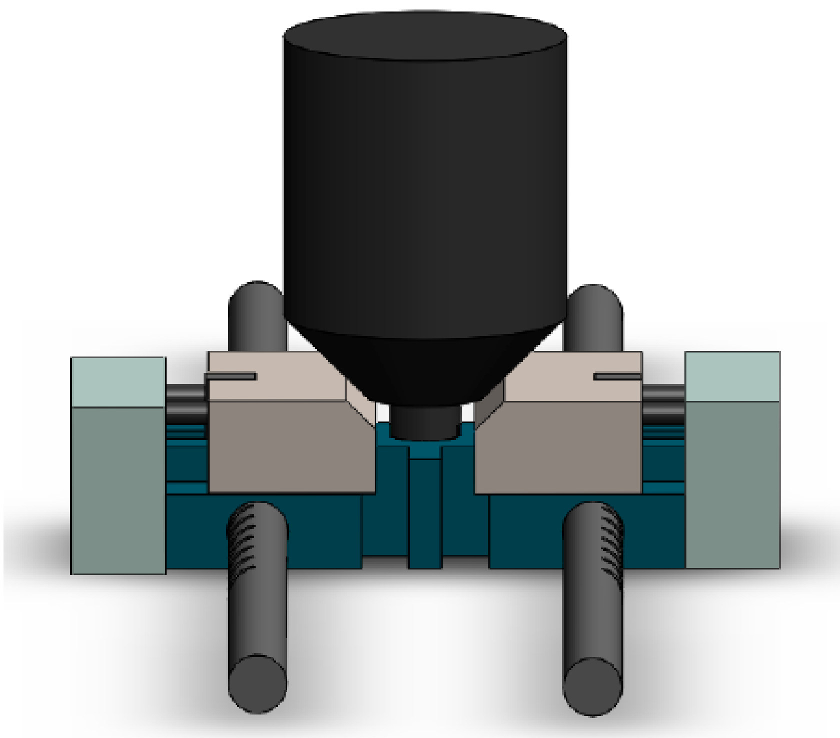
Different control methods: The socket should be able to handle different control methods e.g. hardness, myo-electric, elbow control.

Different terminal devices: The socket should be able to connect with different terminal devices, such as hand, hooks etc.

Cost effective: According Walta et al (1989) the current WILMER socket is cost effective [7]. The new design should be kept around the same price range. Not to expensive materials and components should be used.

Appendix E

Locking mechanism



I. Final concept

The final model consists of 8 components; button, sliders, springs, pins, knives, teethed bars, housing and support for the springs and pins. Figure E.1 shows the 3D image of the whole model and the different parts. Only 6 of the 8 components needed to be produced.

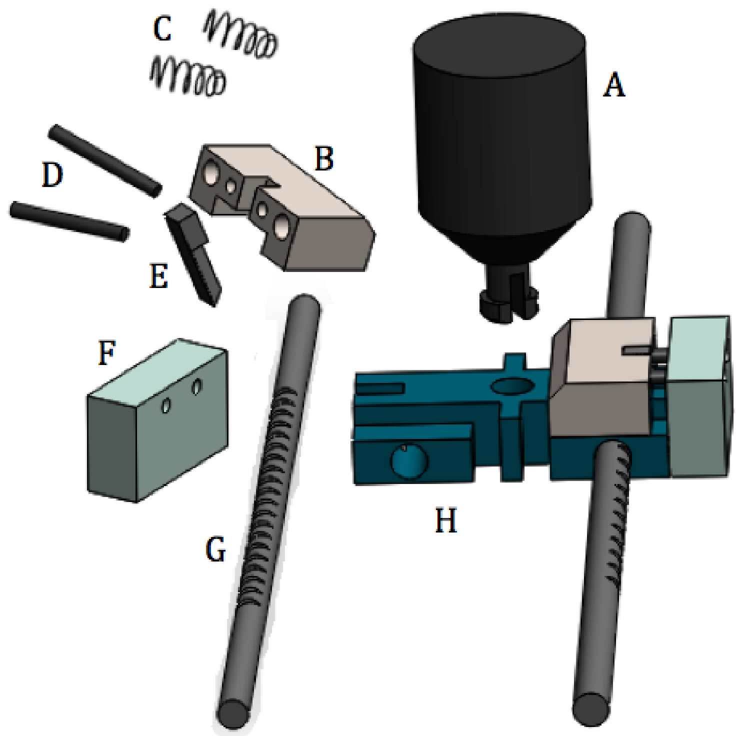


Figure E.1: *3D image of the different parts. A) Button B) Slider C) Springs D) Pins E) Knife F) Support for the springs and pins G) Teeth bar H) Housing.*

1. Housing
Material: Polyvinyl chloride (PVC)
Dimensions: see Appendix G.**??**
Quantity: 1x

The first component is the housing, which is made out of PVC (Figure E.1H and E.2). When heated to maximum 60-degrees, this can be bent in a V-shape (like the original system). In the middle there is a rail to guide the two sliders horizontally and in the center there is a hole for inserting the button.

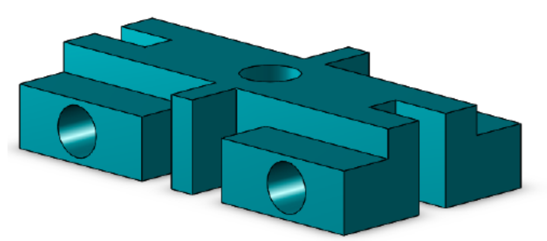


Figure E.2: *The housing.*

2. Button
Material: Delrin
Dimensions: See Appendix G.**??**
Quantity: 1x

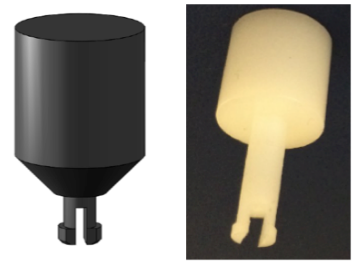


Figure E.3: *The new (left) and original (right) button.*

The second component is the button (left figure in Figure E.3). It has almost the same design as the original locking system (see right figure in Figure E.3). The new button has a 45-degree angle to move the sliders horizontally. The angle of the top edge of the slider is also 45 degrees with the height 1.25mm. Hence, when the button is pressed 1.25mm, the sliders move 1.25mm in the horizontal direction (Figure E.6). The small cylinder (end of the button) is inserted into the hole in the housing (Figure E.2). A 3mm hole is made through this cylinder so it is flexible and easier to insert into the hole. The end of the small cylinder is a little bit ticker than the rest and this is done to ensure that the button does not drop out from the housing. The same concept was also used in the original system.

3. Teethed bars (rods)
Material: Stainless steel 303
Dimensions: $D = 2.5mm$, $h = 0.8mm$
Quantity: 2x

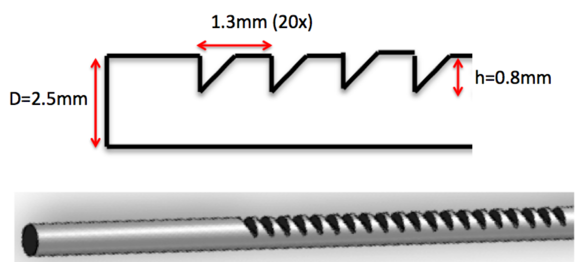


Figure E.4: *Teethed bars.*

The teethed bars were chosen to the same dimensions as the design of Bos et al (2012) [11] with a diameter of 2.5mm and tooth depth of 0.8mm (Figure E.4), thus their produced part could be used for the new design. The bar had 20 different positions (teeth) with an interval of 1.3mm.

4. Slider
Material: Aluminium
Dimensions: see Appendix G.**??**
Quantity: 2x

The fourth component is the sliders. As mentioned before, the angle of the top edge of the slider has a 45-degree angle and a height of 1.25mm and when the button is pressed, the sliders moves 1.25mm in the horizontal direction. The sliders have 2 holes of 1.8mm diameter for the springs and 2 holes of 1.1mm diameter for the 2 pins. On each slider a knife is attached.

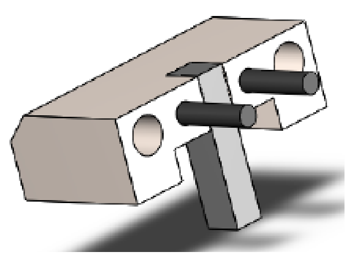


Figure E.5: *The slider, the knife and the 2 pins.*

5. Knife
Material: Stainless steel 304
Dimensions: see Appendix G.**??**
Quantity: 2x

The knife and the slider are two separate components,
but should be glued together. The knife is attached to the end-side of the slider in the middle (Figure E.1E and Figure E.5).

6. Pin
Material: Aluminium
Dimensions: $D = 1mm$, $l = 9mm$
Quantity: 4x

The pins are also separate component and should be glued into the 1.1mm holes inside the sliders (Figure E.1D and Figure E.5). For each slider 2 pins are needed with a diameter of 1mm and length of 9mm. The pins are used to hold the sliders on its place.

7. Springs
Dimensions: $D = d + Dm = 1.8mm$, $l_0 = 9.2mm$
Quantity: 4x

The springs were also ordered and this was done from the website *Tevema.com* [15]. On each slider there are two holes with a diameter of 1.8mm for the springs. In total 4 springs are needed for this mechanism. Since the depth was chosen to 5mm and a diameter of 1.8mm (maximum possible depth and diameter for the slider) a spring was selected that could be a possible choice for the final prototype. To select spring the website *Tevema.com* was used [15]. The parameters of the chosen spring can be seen in Table E.1.

Table E.1: *Parameters of the chosen spring [15].*

d [mm]	Dm [mm]	l_0 [mm]	S_n [mm]	L_n [mm]	F [N]	k [N/mm]
0.2	1.6	9.2	5.38	3.82	1.7	0.32

Each spring was loaded with a force of approximately one 1 N:

$$F = \Delta l \cdot k = (l_0 - l) \cdot k = (9.2 - 6) \cdot 0.32 = 1.024[N] \tag{E.1}$$

where k is the stiffness, l_0 is the free-length and l is the compressed length. It has been chosen to 6mm since the hole in the slider is 5mm and the 1mm is needed so the knife unlocks the system.

8. Support
Material: Aluminium
Dimensions: Appendix G.**??**
Quantity: 2x

The last component is a support for the springs and pins (Figure E.1F). The supports are connected on each side of the housing and two supports are needed for this mechanism. Each support has 2 holes with a of diameter of 1.1 mm so the pins can be inserted. The support is connected on each side of the housing with small screws and when pressing the button the two sliders will move to the horizontal direction and the pins will slide into the support (Figure E.6).

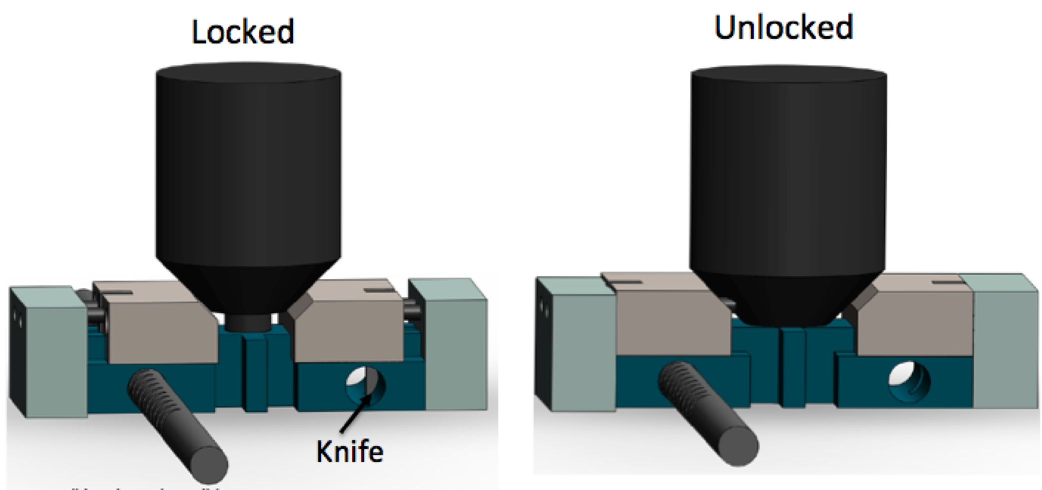


Figure E.6: *When the button is pressed the two sliders with the knives move 1.25mm in the horizontal direction and unlock the system.*

II. Validation of design criteria

Table E.2: *Validation of the design requirements for the new locking mechanism.*

Design criteria	Prototype
Height <7.5mm	7.2mm
Weight <35g	9g
Strength >600N	2·305N
Possible to V-shape	When the housing, made out of PVC, is heated to 60-degrees it is possible to V-shape.
No parts sticking out	When the button is sanded no parts of the mechanism are sticking out.
Easy to operate	The mechanism is possible to operate using only one hand and force needed to unlock the system is 4N.
Waterproof	All parts of the new locking mechanism are waterproof.

Appendix F

Socket

I. Wire mesh connecting methods

This section provides an overview of the different wire mesh connecting methods used in this study followed by images of the samples used during the strength tests for the connecting methods.

I.1 Connecting methods

I.1.1 Adhesive

An adhesive is a substance that binds two surfaced together when it is applied to the material surface, as glue or rubber cement [16]. In this study two different types of adhesive glue were used; hot glue and epoxy resin. Hot glue, also known as hot melt adhesive (HMA) is a form of thermoplastic adhesive. The glue is usually supplied in solid sticks, which is melted with a hot glue gun (Figure F.1). The melting temperature for the glue is usually about 120 degrees [17]. Epoxy resin is a two-component glue, which means that two components need to be mixed to be hardened. The individual components are not adhesive alone, but need to be reacted with another component to become adhesive. During this reacting epoxies are formed, which is a strong adhesive [17].

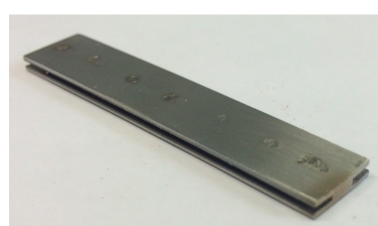
Figure F.1: *The hot glue and hot glue gun [18].*

Figure F.2: *Epoxy resin. [19]*

I.1.2 H-profile

An H-profile is a metal or plastic strip made in an H-shape (Figure F.4a). This can be used to connect two edges to each other by using for example adhesive. Figure F.12 shows the H-profile used by Ravensbergen (2010) to connect the wire mesh edges and Figure F.4b shows the H-profile used in this study.

(a) *Shape of the H-profle [20].*



(b) *Stainless steel H-profile, which was used in this study.*

Figure F.3: *H-profile.*

I.1.3 Soldering

Soldering is a process in which two or more metals are joined together by melting a filler metal (solder) into the connecting point. The solder (filler metal) has a lower melting point than the metals that are joined together. There are two different types of soldering; hard soldering and soft soldering. In the hard soldering process high temperature is needed (above 450 degrees). Silver can be used as filler material, which was also done in this study (Figure F.11). Soft soldering is commonly used for joining parts with lower melting point that might get damaged or deformed at high temperature. It uses tin alloy as a solder material and the melting point of this material is below 400 degrees [21].

(a) *Hard soldering with silver [10].* **(b)** *Soft soldering device [22].*

Figure F.4: *Hard and soft soldering.*

I.1.4 Point welding

Point welding, also known as spot welding, resistance spot welding (RSW) or resistance welding (RW) is a welding process, where two pieces of metal surfaces are joined together under pressure exerted by electrodes. During point welding an electric current is passed through the welding metal and the resistance to electric current creates enough heat to weld the metals. This process is used to weld together two or more overlapping metal pieces [24].

Figure F.5 shows the point-welding device [23] and the point welded wire mesh sample can be seen in Figure F.9.

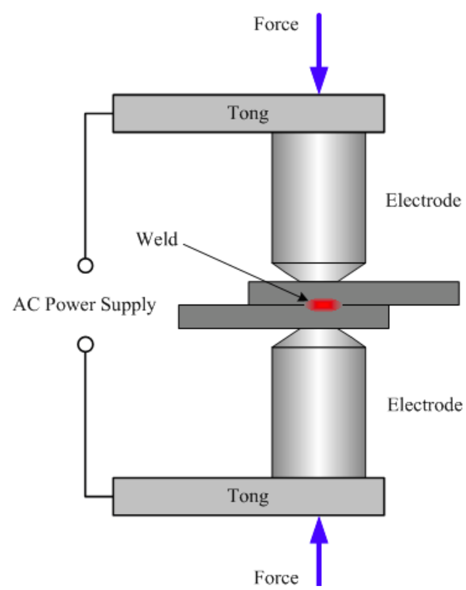


Figure F.5: *Point welding device [23]*

I.2 Strength test samples

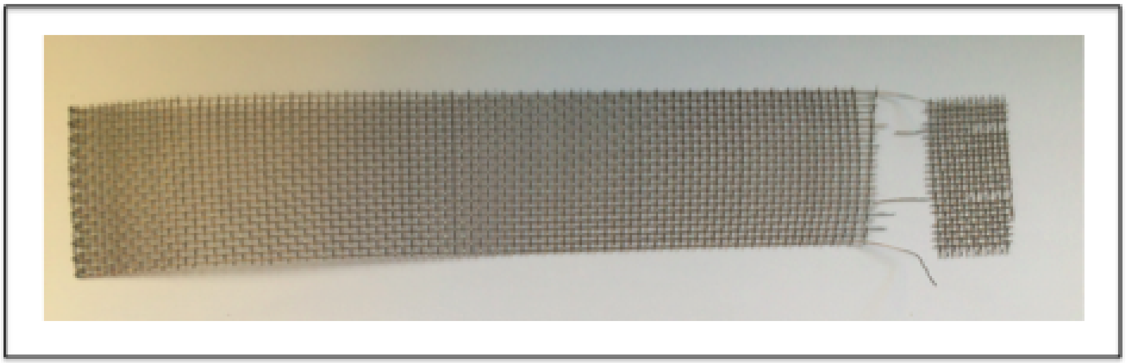
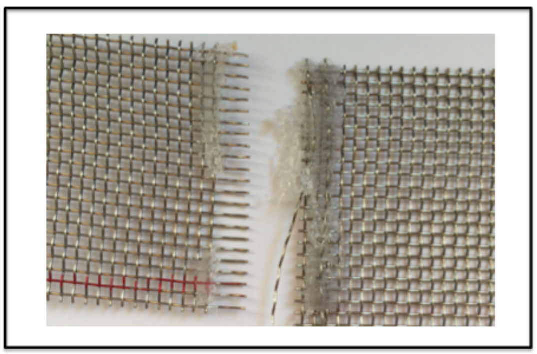
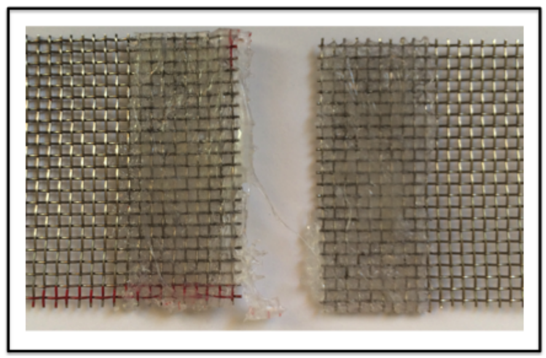


Figure F.6: *Wire mesh sample.*

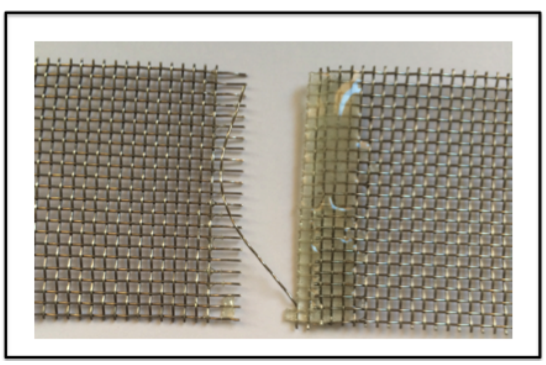


(a) *Hot glue - tensile.*

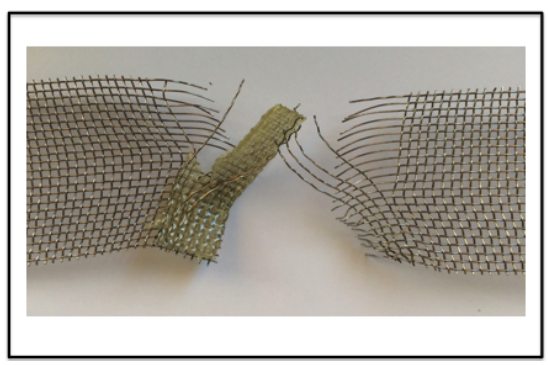


(b) *Hot glue - shear.*

Figure F.7: *Wire mesh connected with hot glue.*

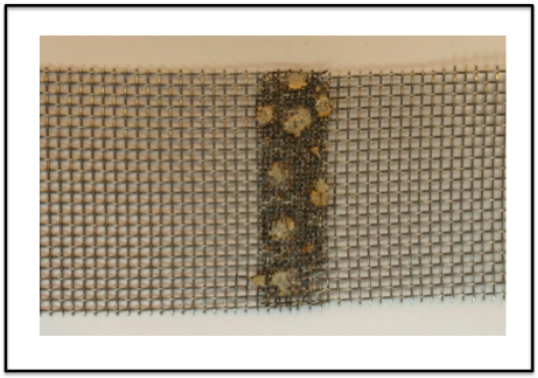


(a) *Epoxy resin - tensile.*

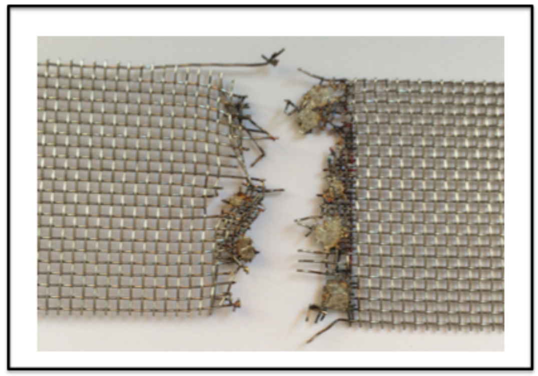


(b) *Epoxy resin - shear.*

Figure F.8: *Wire mesh connected with epoxy resin adhesive.*

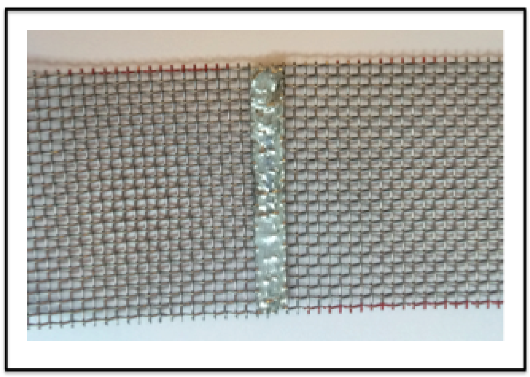


(a) *Point welding before - shear.*

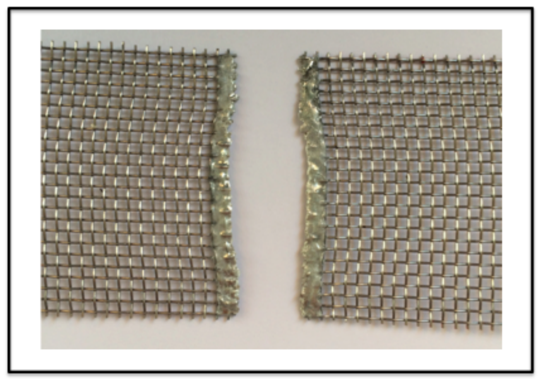


(b) *Point welding after - shear.*

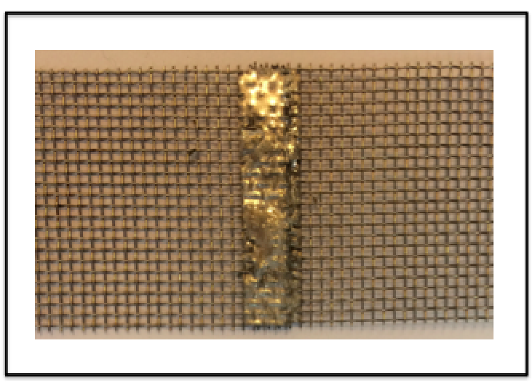
Figure F.9: *Wire mesh connected with point welding.*



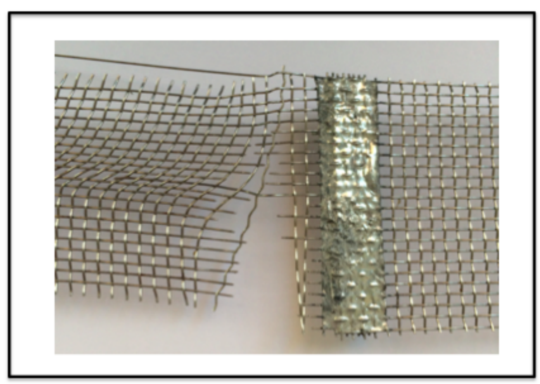
(a) *Soft soldering before - tensile.*



(b) *Soft soldering after - tensile.*

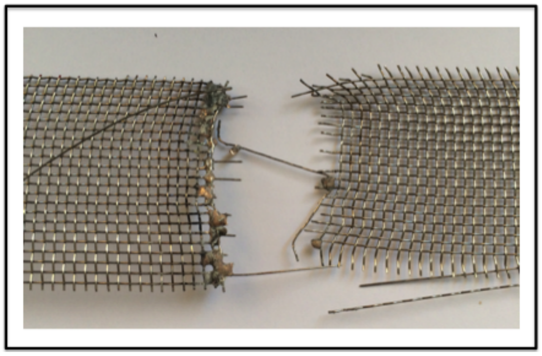


(c) *Soft soldering before - shear.*

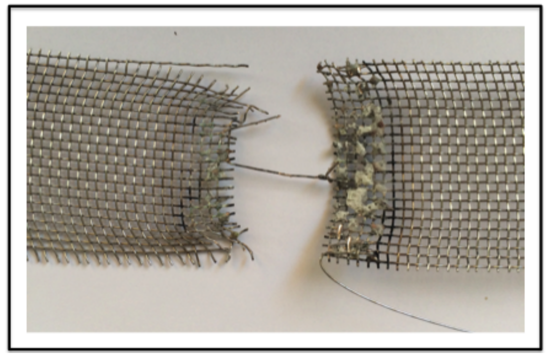


(d) *Soft soldering after - shear.*

Figure F.10: *Wire mesh connected with soft soldering.*

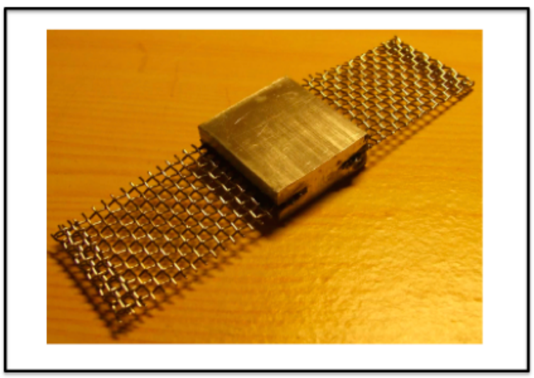


(a) *Hard soldering - tensile.*

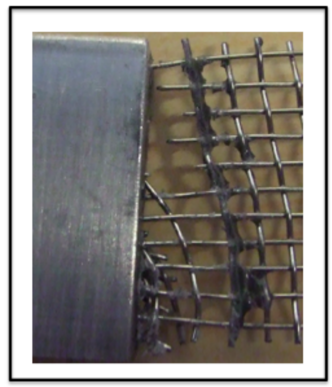


(b) *Hard soldering - shear.*

Figure F.11: *Wire mesh connected with hard soldering.*



(a) *H-profile before - shear.*



(b) *H-profile after- shear.*

Figure F.12: *Wire mesh connected with an H-profile [6].*

II. Fitting procedure

In this section is the fitting procedure of the new WILMER Open Socket is described step-by-step. The materials needed to produce the new WILMER socket can be seen in Figure F.13.

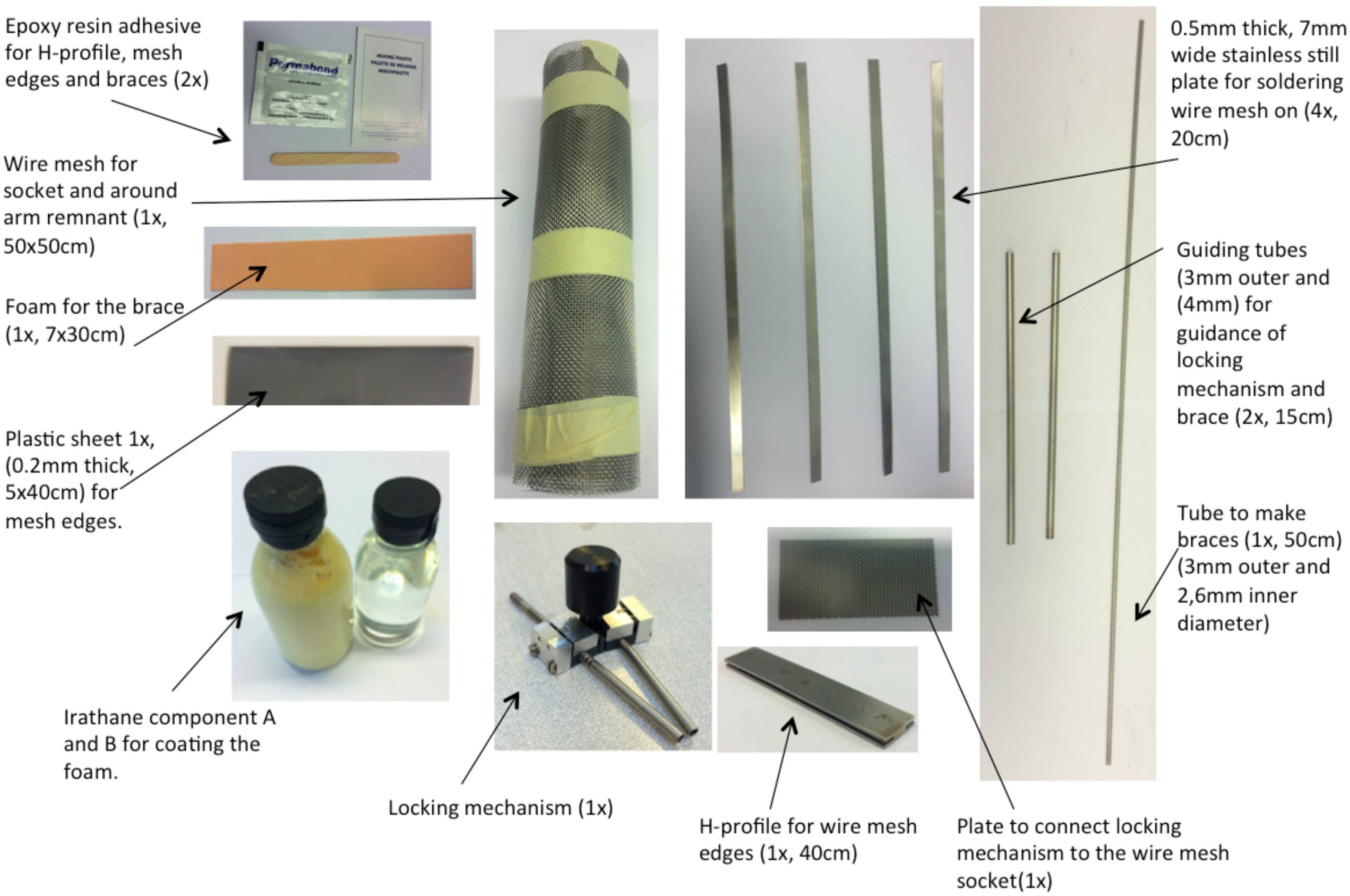
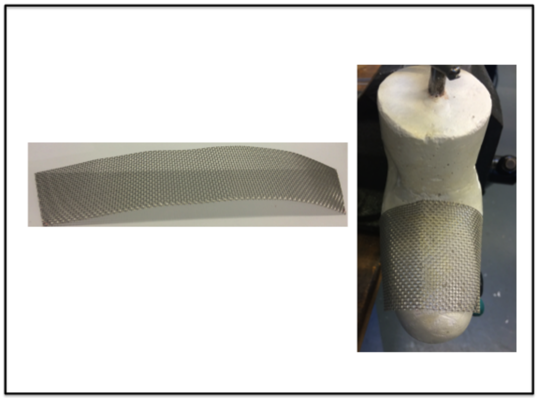


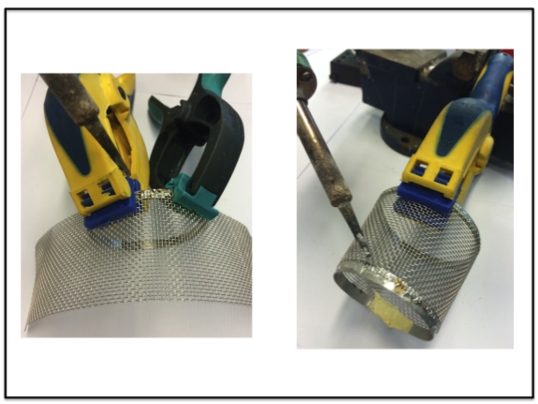
Figure F.13: *Material and parts needed to fabricate the new WILMER Open Socket.*

Fitting procedure of the new WILMER Open Socket

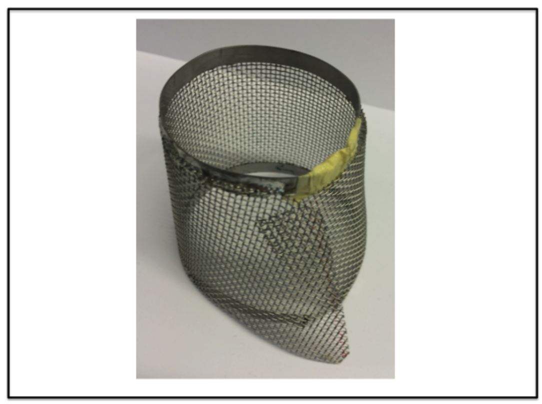


1. Cut a small piece of wire mesh so it fits around the arm remnant.

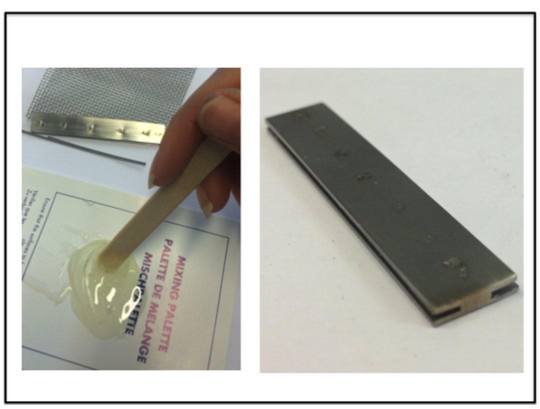
2. Deform two rings of the stainless steel plate; one proximal the arm remnant and one distal.



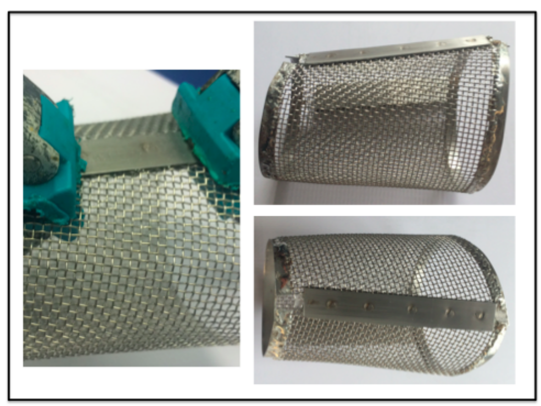
3. Solder the wire mesh to the two stainless steel rings.



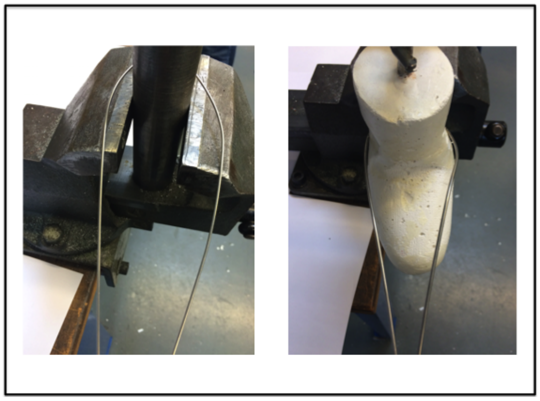
4. Cut the wire mesh rests.



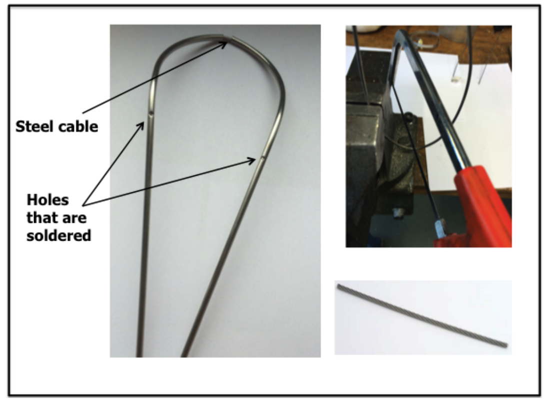
5. Use an H-profile and connect the mesh with two component glue (epoxy resin).



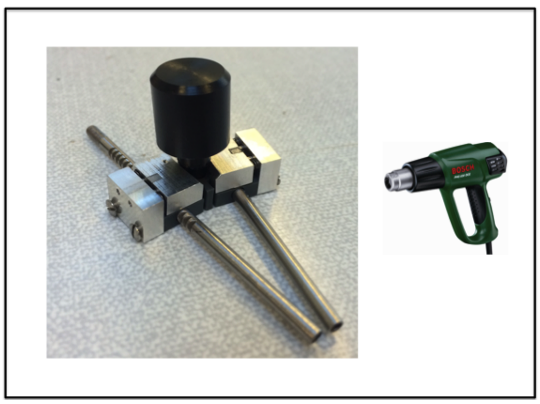
6. Wire mesh connected with an H-profile.



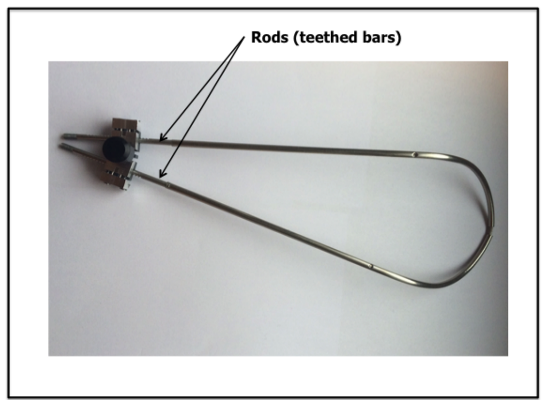
7. Deform the 3mm tube to a brace so it fits around the arm.



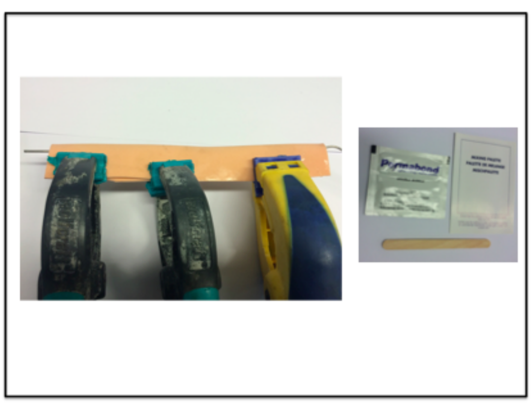
8. Cut the braces in half, insert a small piece of steel cable, make two small holes and solder it.



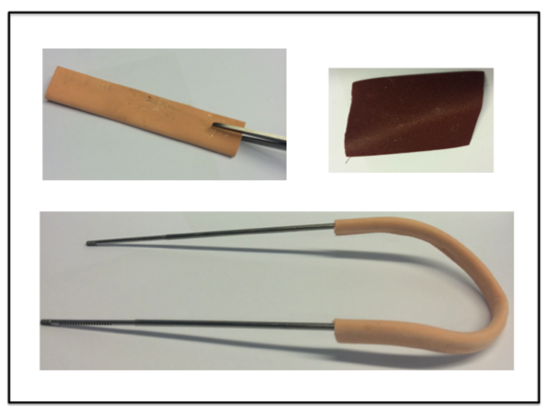
9. Bend the locking mechanism by applying some heat to it with heat a gun.



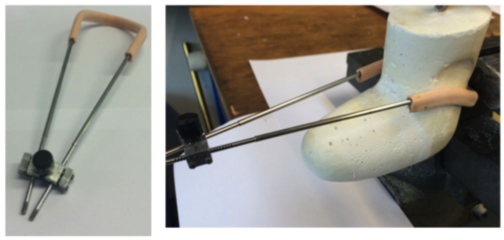
10. Glue or solder the two rods from the locking mechanism inside the brace's tubes.



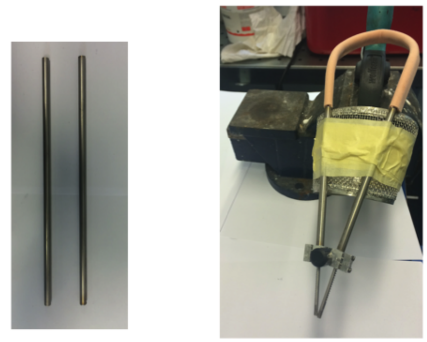
11. Take one piece of foam, glue the corners together with two component adhesive.



12. Cut the foam, insert the brace inside it and sand the foam.

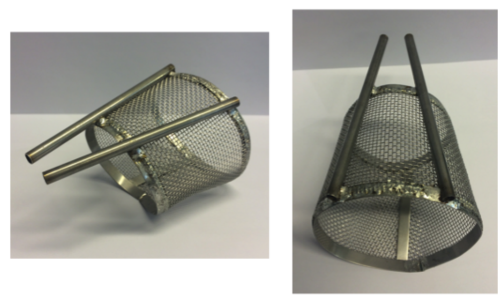


13. The locking mechanism and the brace.

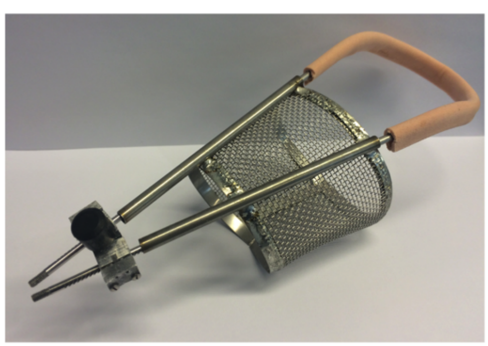


14. Insert the two 4mm guiding tubes inside the brace and fix it to the small socket with paper tape.

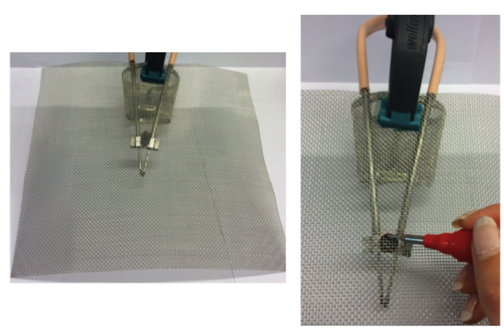
15. Solder the two guiding tubes to the small wire mesh socket.



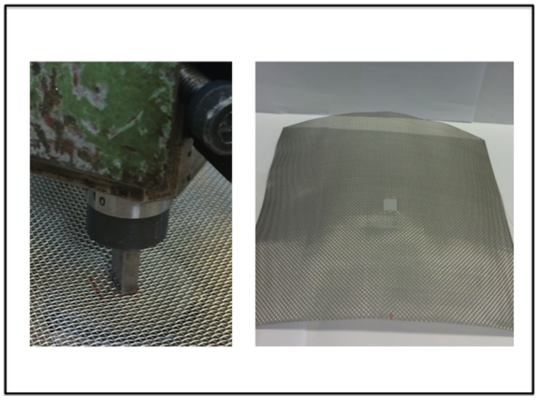
16. The two V-shaped guiding tubes soldered to the small arm socket.



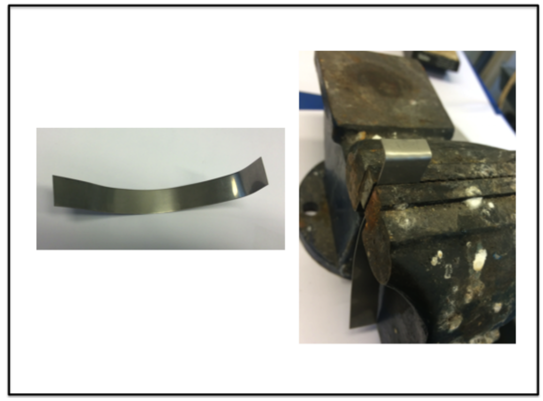
17. Locking mechanism and the condyle brace inserted into the guiding tubes.



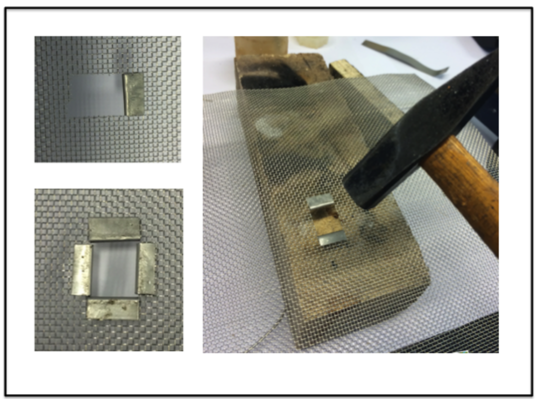
18. Cut a piece of wire mesh for the socket and measure the distance to the locking mechanism's button.



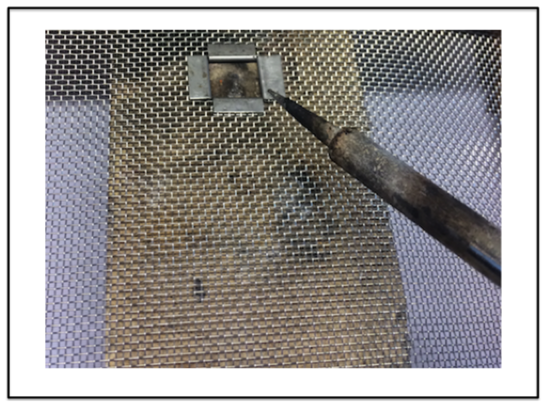
19. Make a small hole inside the wire mesh for the button.



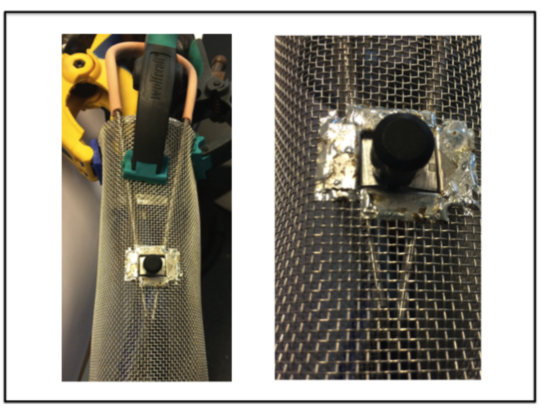
20. Cut 4 small piece stainless steel plates for the button's sharp edges.



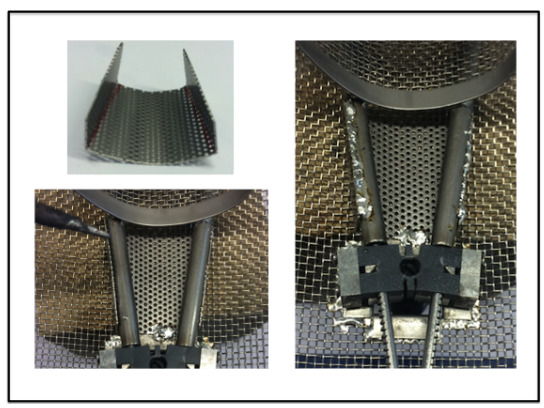
21. Bend it and place around the edges.



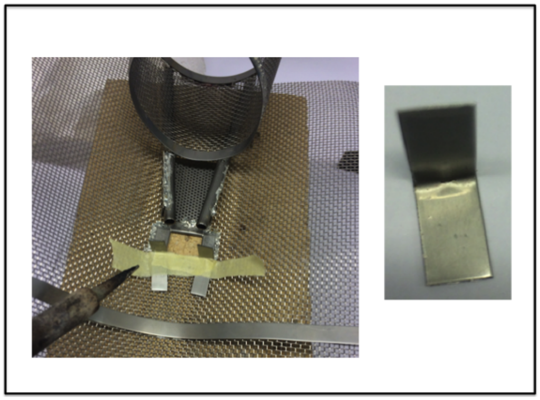
22. Solder or glue the 4 plates to the wire mesh socket.



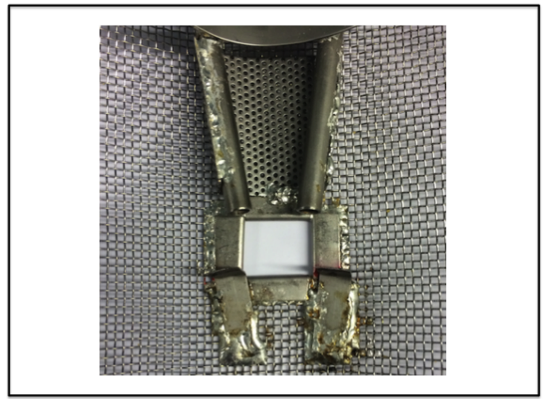
23. Steel plates soldered to the long wire mesh socket.



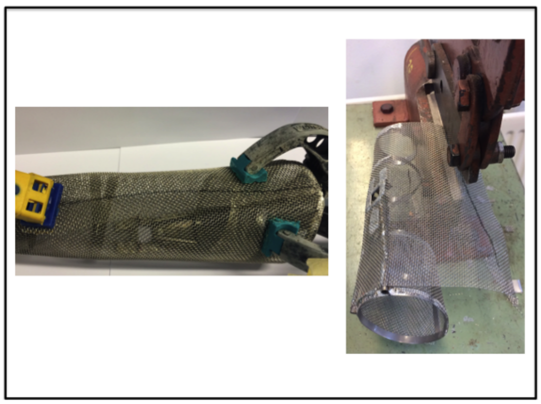
24. Bend the metal plate and solder it to the 2 tubes and the socket.



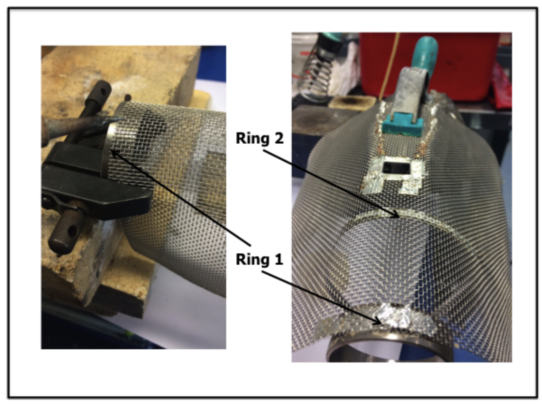
25. Cut 2 small stainless steel plates and solder it to the socket so the locking mechanism is fixed.



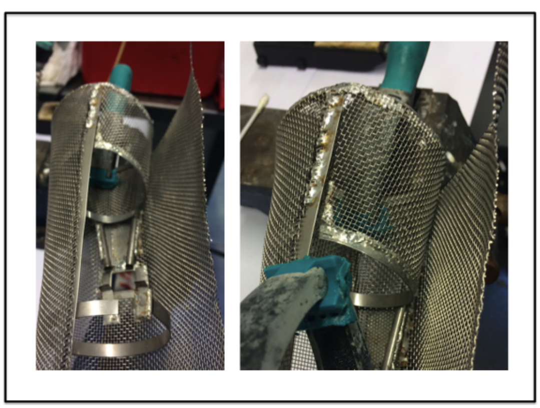
26. Steel plates soldered to the wire mesh to keep the mechanism fixed.



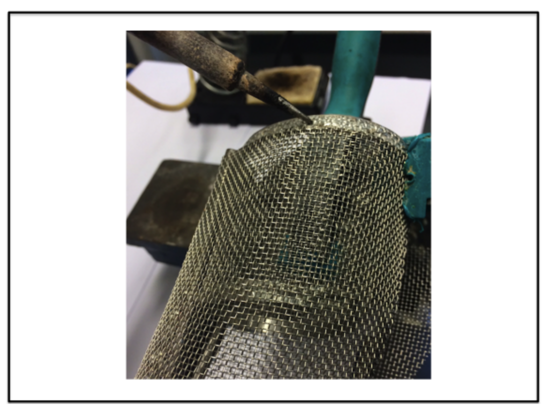
27. Connect the socket with clamps and cut rests of the mesh.



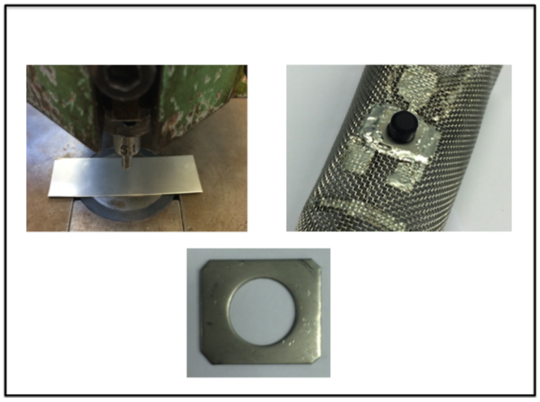
28. Insert 2 rings; one for the terminal device and one for support, and solder it.



29. Insert a small strip of stainless steel plate and connect the wire mesh by soldering or with an H-profile, same way it was done in step 5 and 6.

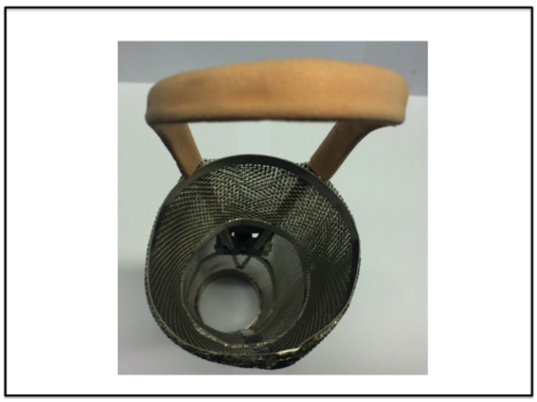


30. Solder the socket's wire mesh edges to the small socket.

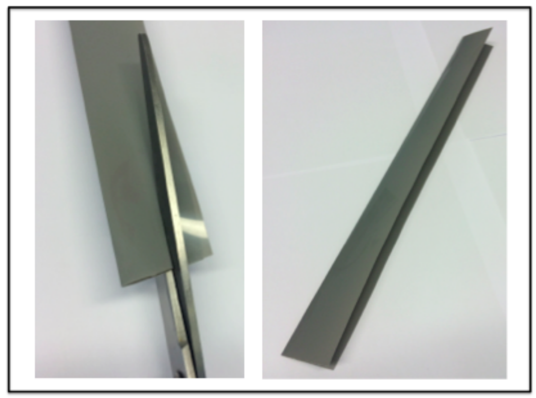


31. *Make a 10mm hole inside a stainless steel plate and solder it to the socket.*

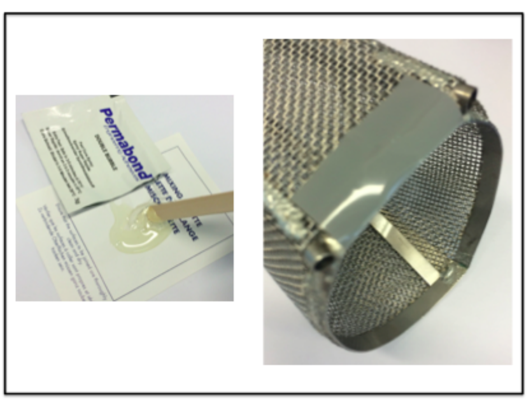
32. *The stainless steel wire mesh socket.*



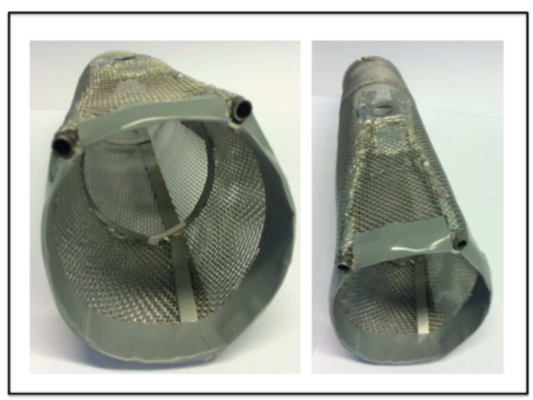
33. *Inside the socket.*



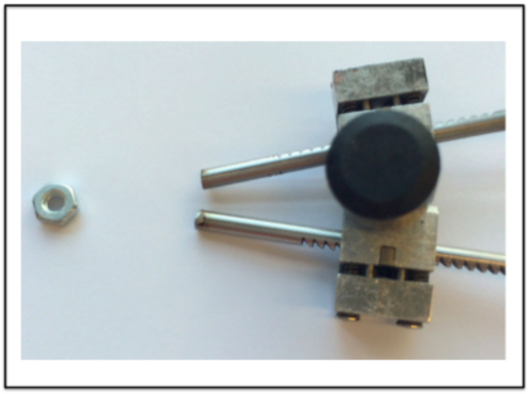
34. *Cut a small piece of the plastic sheet (0.2mm thick) for the socket's edges.*



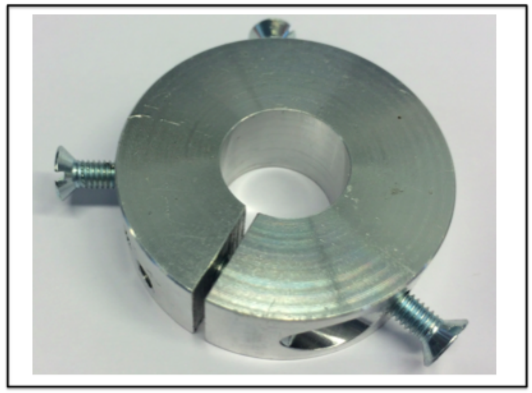
35. *Glue the plastic sheet to the socket's sharp edges with epoxy resin.*



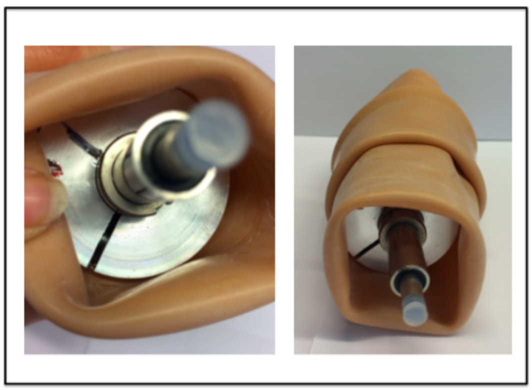
36. *Wire mesh edges covered with plastic.*



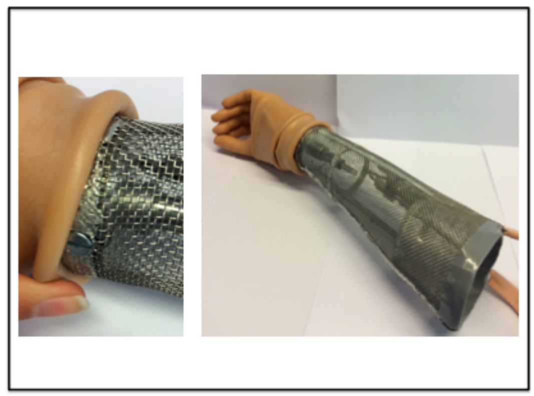
37. Use a nut bolt at the edge of the 2 teethed bars so the locking mechanism does not go out during donning and doffing of the socket.



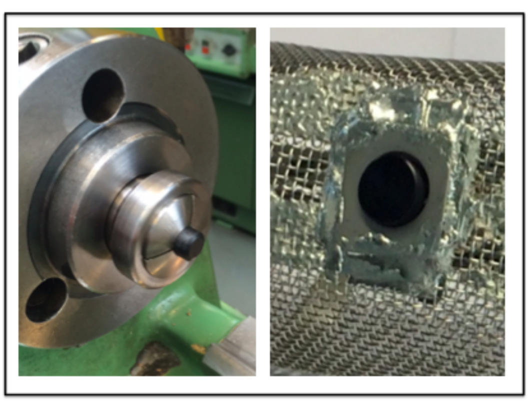
38. Use the designed wrist joint to connect the terminal device to the socket.



39. Insert the terminal device (hand) covered with forearm shell inside the wirst joint and connect it to the socket.



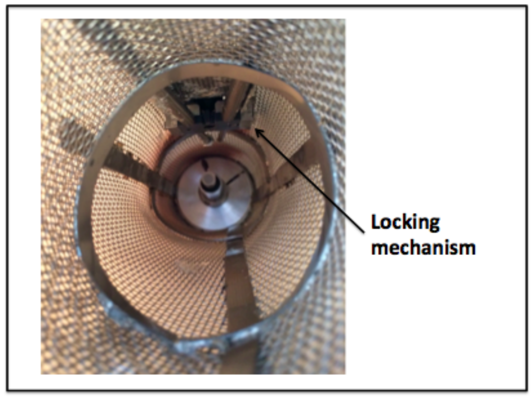
40. Terminal device (hand) connected to the socket.



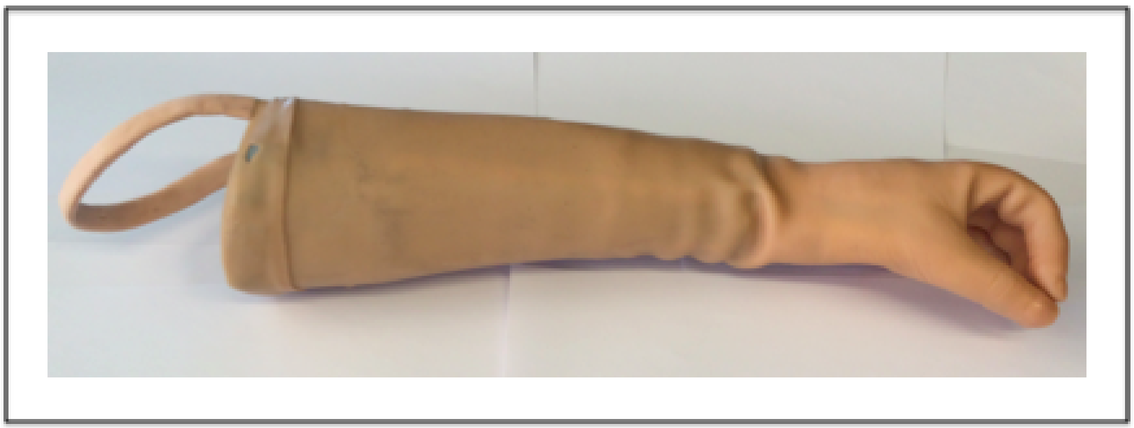
41. Make the button shorter, either by sanding it or cut it, so it does not stick out from the socket.

42. Pull the forearm shell over the socket so it covers the wire mesh.

43. Coat the foam braces with with irathane to protect against abrasion.



44. Inside the socket.



45. Final prototype: stainless steel wire mesh socket covered with a forearm shell.

III. Validation of design criteria

Table F.1: *Validation of the design criteria for the new WILMER Open Socket.*

Design criteria	Prototype
Transition <5mm	$\approx$ 4mm. The transition between the socket and the limb is <5mm everywhere except at the guiding tubes (7mm).
Adjustable	With the locking mechanism the condyle brace can be adjusted into one of the 20 different positions with an interval of 1.3mm.
Easy donning and doffing	The socket can easily be donned and doffed using only one hand.
Self-suspension	The prosthetic user can self attached the socket to the residual limb using one hand.
Sufficient ventilation	The selected wire mesh has a transmittance of 60%. The permeability of the wire mesh covered with forearm shell could not be tested.
Lightweight (<200g)	180g
Strength >100N	Radial strength: 122N. Axial strength: 108N
Comfortable material	The materials used are biocompatible with the skin, easy to clean, smooth and have no sharp edges.
Lifelike	The forearm shell covering the wire mesh gives a more natural looking prothesis and no parts are sticking out from the socket.
Easy fitting procedure	Since the socket uses similar fitting procedure like the original WILMER socket, the new socket can be fitted in a standard prosthetic facility. However, some of the steps in the fitting procedure need to be simplified.
Waterproof	The socket is made out of waterproof materials.
Different control methods	The socket can handle different control methods.
Different terminal devices	The socket can be connected to different terminal devices.
Cost effective	The socket is cost effective. No expensive materials are used in the socket.

Appendix G

Engineering drawings

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