CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF BIOMEDICAL ENGINEERING

Department of Biomedical Technology

The design of a bow holder for a 7-year-old girl with a disability in her left hand

Master thesis

Study programme: CEMACUBE. European Master's in biomedical engineering. Specialization: Medical Device Design.

Study branch: Biomedical Engineering

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MASTER'S THESIS ASSIGNMENT

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II. MASTER'S THESIS DETAILS

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Guidelines:

Analyse the biomechanics involved with cello/violin playing. Design a bow holder that can be used by a person missing portions of their arm. Prepare a technical design in Fusion 360 programme. Refine technical parameters for fabrication of a trial. Evaluate designed trial.

Bibliography / sources:

[1] Megan Hofmann, Jeffrey Harris, Scott E. Hudson, Jennifer Mankoff, Helping Hands: Requirements for a Prototyping Methodology for Upper-limb Prosthetics Users, ed. 1 ed. , 2016, ACM New York, NY, USA, 978-1-4503-3362-7
[2] S. Duprey, B. Michaud & M. Begon, Muscular activity variations of the right bowing arm of the violin player, Computer Methods in Biomechanics and Biomedical Engineering, ročník 20, číslo S1, 2017, 71-72 s.

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Declaration

I hereby declare that I have completed this thesis having the topic "The design of a bow holder for a 7-year-old girl with a disability in her left hand" independently and I have included a full list of used references.

I do not have a compelling reason against the use of this thesis within the meaning of Section 60 of the Act No 121/2000 Sb., on copyright and rights related to copyright and on amendment to some other acts (The Copyright Act), as amended.

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Klíčová slova

Specifická protetika, nízkonákladový, design zaměřený na člověka, rychlé prototypování, 3D tisk, postižení končetin, držák smyčce.

Key words

Task specific prosthetics, low-cost, human-centred design, rapid prototyping, 3D printing, limb difference, bow holder device.

Abstrakt

Lidé s postižením končetin, kteří chtějí hrát na hudební nástroje, mají v této oblasti velmi omezené možnosti, které by jim umožnily hru na hudební nástroj. Vzhledem k omezeným finančním zdrojům a omezené dostupnosti speciálních pomůcek je pro ně velmi obtížné hrát na hudební nástroje.

V této práci je popsán návrh a vývoj držáku smyčce na čelo pro sedmiletou dívku s postižením levé ruky. Práce je zaměřena na design a vývoj prototypu pomůcky, která by umožnila dívce hru na čelo, a zároveň byla dívkou akceptována a plně využívána. Cílem této práce bylo porozumět základním potřebám a požadavkům dívky/uživatelka, které povedou k vytvoření pohodlného, snadno použitelného a levného prototypu držáku pro smyčec. Přehled literatury a návrh a realizace prvního prototypu byly použity k vytvoření seznamu specifických požadavků na adaptační zařízení, které by mělo splnit požadovaný účel. V rámci syntézy I a syntézy II byly v CAD vytvořeny různé návrhy pomocí technologie Fusion 360, které byly vyrobeny pomocí výrobních technologií, jako je 3D tisk a rychlé prototypování.

Při řešení diplomové práce byly specifikovány vlastnosti, které jsou nezbytné k vytvoření funkčního konceptu, jako je úhel zápěstí, vzdálenost prstů a požadované stupně volnosti. Nová designová řešení byla navržena ve verzi Fusion 360 a konkrétně FDM byla vyrobena z dostupných levných materiálů. Dále byla popsána metoda získání 3D modelu končetin uživatelky.

Finální konstrukce je modulární zařízení, které se skládá ze 4 částí, které jsou vzájemně propojeny jednoduchými montážními mechanismy, které splňují požadavky získané v uživatelském pokusu s prvním prototypem držáku. Výsledný prototyp byl úspěšně vytištěn a vyroben ve 3D. Budoucí práce bude zahrnovat testování prototypů a provedení nezbytných optimalizací.

Abstract

People with limb difference aspiring to play musical instruments have a very limited choice of devices that allow them to reach their potential. Due to their limited resources and low accessibility to a specialist design and manufacturing equipment, it is not easy for them to tackle their task specific issues.

A human-centred design thinking approach has been applied to develop this master project which describes the design and production process of a cello-bow holder for 7-year old girl with a left-hand disability. The goal of this work was to develop a deeper understanding of the requirements and practices needed to create a comfortable, easy to use and low-cost bow holder body-powered device. Literature review and the realization of a user trial were used to create a list of specific requirements for a bowing adaptive device should have to meet the goal. Along Synthesis I and Synthesis II different designs were designed in CAD using Fusion 360 and fabricated using manufacturing technologies such as 3D printing and rapid prototyping.

We have specified the characteristics needed by the user to design a final concept such as wrist angle, finger distance and degrees of freedom needed. Novel design solutions were designed in Fusion 360 and specifically FDM fabricated using different low-cost materials. Furthermore, a 3D model acquisition method for obtaining 3D models from body extremities was described.

The final design is a modular body powered device in 4 parts connected to each other with easy assembly mechanisms fulfilling the requirements obtain in the user trial. The final prototype was successfully 3D printed and manufactured. Future work will involve testing the prototypes and carrying out its necessary optimizations.

Acknowledgements

I have been extremely fortunate to have had the support of the department family friends and colleagues near and far. Without this support this thesis would not have been possible.

I would like to express my special thanks of gratitude to the user of this project and her family, for their time, patience and consideration while I was developing the cello bow holder device and for their implication and help during the User Trial. As well, I would like to say thanks to Rachel Wolffsohn, the head of the OHMI charity, for her time and useful comments during the development of this thesis.

Foremost, I would like to express my sincere gratitude to my advisor Prof. Dominic Eggbeer who provided me with an opportunity to join his team, support and guidance, and who has given me access to his 3D printers and PDR research facilities during these last months.

Thanks to the PDR team for the obtained knowledge from their professionals. Especially to Katie Beverley, Emily Bilbie, Graham Jones, and Allistair Ruff for sharing their time with me giving me advice.

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My family for supporting me during these last years and giving me the opportunity to study and learn from an international environment.

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Introduction

People with limb difference aspiring to play musical instruments have a very limited choice of devices that allow them to reach their potential. In Europe, 14% of the people have a disability [1]. If just a few percent of them want to have the possibility of making music, they should have it. People with disabilities are unsupported and undermined, and sometimes they are left without a voice. Some of them want to have a career in music and become a professional instrument player, but they cannot because no tool exists for them just because no musical instruments have been designed with them in mind. Existing solutions are hard to come by, due to people limited access to design and manufacturing expertise necessary to develop highly individualised solutions. Through design and technology, it is possible to increase the social equality and opportunities [2].

Figure 1. Picture taken during the User trial. Manchester. 28/05/2019

As a musician and engineer, I have chosen this project to connect and provide current technology and rapid prototyping resources to a specific person, which suffers from a rare blood vessel anomaly called Capillary lymphatic venous malformations (CLVMs) in her left hand and wants to play the cello as her father does. This project aim is to use technology innovation to give to this girl the chance of making music by developing a deeper understanding of the technical requirements and practices needed to create a comfortable, easy to use and low-cost bow holder body-powered device [2]. With the help of this device she will be able to reproduce the balance and holding/gripping movements necessary for bowing.

Considering that to make music is a skill that not only offers happiness, but also challenges and stimulates the brain, bring us to the fact that everyone should have the opportunity to make music. That will improve disable people quality of life and therefore it will benefit the society.

Privacy issues were handled in advance. The consent form is attached at the end of the Ethic section of this project.

1 Layout of the project

A methodical human centre design process has been done to design a specific bow holder. This process was divided into the following sections:

- LITERATURE REVIEW – It shows the background information researched along the project to better understand the problem and its possible solutions.
- STATE OF THE ART- It shows current bow holder designs and its deficiencies.
- CHAPTER 1. Analysis phase- The goals and design problems are analysed to set up an overall direction for the project.
- CHAPTER 2. Design criteria- In this chapter a list of requirements that the solution must satisfy and a list of wishes the design might fulfil will be described.
- CHAPTER 3. Synthesis phase I- different draws and models of the ideas are developed to estimate and define the expected properties during of your design
- CHAPTER 4. User trial- In this chapter a description of the user trial is developed. Different prototypes developed in Synthesis I were test with the user and deeper information was obtained from questionnaires and observations from the end user and her family,
- CHAPTER 5. 3D Model of a hand- In this chapter it is documented a low-cost and easy method to obtain a 3D model of a hand.
- CHAPTER 6. Synthesis II- In this chapter, the new specific requirements will be considered to develop a new round of bow holder pre-concepts to select a final concept. The carefully chosen concept is further detailed and developed.
- CHAPTER 7. Evaluation- at this stage it is brought the design criteria to evaluate the design and the conclusions are established.

Literature review

In this section is explained the necessary background literature research founded to develop this project. From basic anatomy and epidemiology definitions to the biomechanics related with bowing, parts for the violin/cello bow and current bow holders' designs.

1 Lymphatic venous malformation

The end user was born with a lymphatic venous malformation which has change and evolved as she has grown- although the hand has remained unchanged. For this reason, with the aim of getting to know in a better way her condition, literature research related with capillary lymphatic venous malformations was studied.

> *"Capillary lymphatic venous malformations (CLVMs) are rare blood vessel anomalies characterized by an abnormal network of capillaries, lymphatic vessels and veins. Patients with CLVMs have a localized or diffuse capillary malformation (port-wine birthmark) that overlies venous and lymphatic malformations."* [3]

Each case is different depending on where the pathology is located, which is the proportion of the affected vascular components (capillaries, veins and lymphatic vessels) and which body structures are involved. Depending on these three factors it can be found different appearances and complications. For instance, some patients with a combined malformation might have excessive tissue growth and irregular bone growth. Overgrowth frequently affects the extremities but may occur in other zones including the internal organs. This abnormal soft tissue and bone growth may result in shape variations in the limbs [3].

1 **Description and biomechanics related with bowing**

a. **The bow anatomy and its standard dimensions**

Table 1. Cello bow sizes [4]

Cello Size	Bow Length
1/4	23.75"
1/2	25.5"
3/4	27"
4/4	28"

Bow is one of the most important parts in the bow string instrument family. Bowing provides an individual character and timbre to the instrument [5]. As we can see in Table 1, the four standard different lengths of a bow. Figure 2 shows the different parts of a bow. The adult standard bow has a length of 28'' and generally, all of them have an octagonal grip section and their average weight goes from 60-40 grams. [6]

Figure 2. Bow parts [7]

Figure 3 shows the mechanism of the frog. The screw is used to tighten and loosen the hair of the bow. This movement of the frog regulates the tension of the hair and let us to separate the frog from the stick [8].

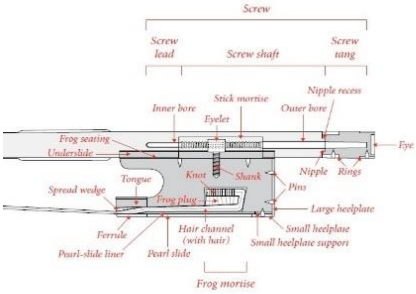


Figure 3. Cross section. Internal mechanisim of the bow. [8]

b. Bow Hand technique

Classically the bow is played by the right hand which holds and controls the duration and character of the notes. Ideally the bow is moved from left to right across the strings in a perpendicular direction. Figure 4 shows that the shape of the hand while holding the bow should resemble that of its relaxed state, with all fingers curved, including the thumb. The bow should be held with all five fingers of the right hand, having the thumb in an opposed position in relation with the other fingers. The bow is normally pinched between the middle two fingers and thumb, while the index and pinkie fingers counter balance each other on their respective sides [9]. Index finger is usually used to provide the desired pressure into the strings, and it has an important role while using different bowing techniques [10].

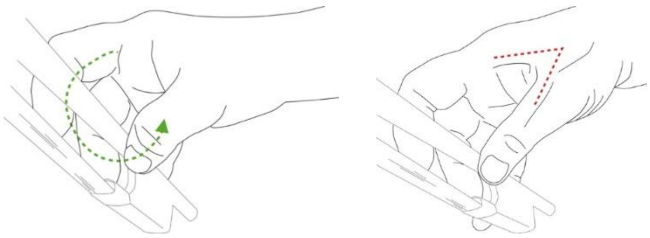


Figure 4. Classical position while holding a bow [11]

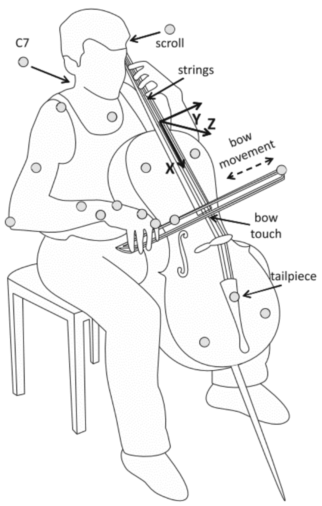
The transmission of weight from the arm to the bow happens through the pronation (inward rotation) of the forearm, which pushes the index finger, mainly, and the middle finger, to a lesser extent, onto the bow. The necessary counterforce is provided by the thumb which should ideally be inactive acting as a support. The other remaining two fingers are used to help maintaining the angle and balance of the bow to the string and are critical to controlling the bow when it is off the string. Additionally, flexibility of the wrist is necessary when changing the bow direction from up-bow to down-bow and vice versa. Furthermore, the wrist is used to accomplish the horizontal movement of the bow for very fast bow movements. On the other hand, when the whole length of the bow is used, arm and wrist actions are combined to achieve a good sound and control [9].

c. Forces and sound production

Tone production and volume of sound depend on a combination of several factors. The three most important ones are: bow speed, weight applied to the string and point of contact of the bow hair with the string. The closer to the bridge the string is bowed, the more projecting and brighter the tone, with the extreme producing a metallic, shimmery sound. If bowing closer to the fingerboard, the sound produced will be softer and less defined [9]. To achieve a successful bowing and tune of the strings, there are two main sources of motion. First, the muscle and neuro systems provide the main control of the bow along the strings. Second, the own weight of the arm/hand provides the necessary contact pressure needed in bowing. Obtaining the better results while muscles are relaxed but still with bow control [9]. When we change from string to string, without lateral up and down movements, shoulder provides the larger range of motion, while the elbow remains almost the same. For shoulder and elbow joints larger groups of muscles are needed while for the wrist and fingers smaller groups of muscles are used to accomplish slighter and finer movements [9]. Bow technique is very important, in muscle activity and bow control. It is proof than experts, cello/violin players with a good technique, need less amount of muscle group activations than new players. The more arm's weight can go into the bow, the fuller sound and more relax the player. It is needed still to squeeze the index against the thumb and keep a balance, but weight transmission will encourage a freer motion than muscle pressure [12].

a. Biomechanical model

Coordinate axis are defined; x-axis goes from the scroll to the tail piece markers as you can see in Figure 6; y-axis is located orthogonal to the strings and parallel to the from plane; and z-axis is set perpendicular to the front plane [13].



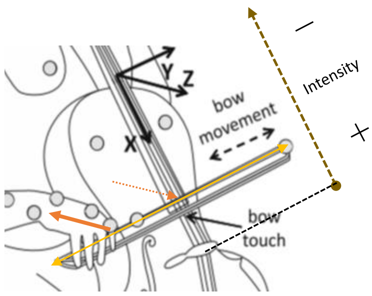


Figure 5. Biomechanical parameters involved in bowing

Figure 6. Cello bowing set-up.

- The x-axis describes the contact point between the strings and the hair bow. Intensity changes along this axe, obtaining a stronger sound as closer as it is to the bridge and poorer as far as it is from the bridge.
- The y-axis defines the bow lateral displacement, up-down movement, being the maximum distance the bow hair length.
- The z-axis has a minimum displacement, but very important one. It controls the strain onto the bow, the arm/hand weight into the bow.

2 State of the Art

Bow holders and task specific prosthesis have been studied and analysed to understand weaknesses and strengths from these devices. Most of these task specific prosthetics are made for amputees or disable users with a missing hand, not considering the end-user's fingers or digits possibilities. Figure 7 shows the current bow holder devices found.

a) "The spatula bow adaptation" or Adrian's spatula. Figure 7 (A).

Adrian Anantawan is a Canadian born violinist and educator with a degree of music from the Curtis institute, Yale University and Harvard Graduate School of Education [14]. Adrian is a professional violin player, which has got his bow holder adaptation thanks to an engineer at the Bloorview Kids Rehabilitation Hospital in Toronto. This bow holder consists of an aircraft grade aluminium bow attachment designed in CAD which is attached to the bow and a socket with a spatula end-shape made originally off a plastic cast and the rubber part of a shoe. It is a simple and light device with a perfect fit for its user. It is stated by the user that having a light device helps him to feel and control the intensity on the string. Moreover, the spatula places the arm directly into the bow which increases his amount of control. The end-user does not have a functional wrist and the device allows him to use 2/3 of the bow length. Nevertheless, he uses his own bowing style to explore different bowing options. Adrian claims that "Each adaptation should be unique, and the best bow adaptation is the one that gives the player the most control and freedom to the user" [14] [15].

a) "Violin prosthetic arm". Figure 7 (B).

This prosthetic arm was designed by Mona Elkholy, Abdelrahman Gouda, and Ella Novoselsky based on the George Mason University for an 11-year-old girl with a missing hand and wrist. This design has considered aesthetic concepts as the user's favourite colour. It is designed in 3 modules. The end of the prosthetic is fixed to the bow and the device is connected to the arm by straps which increase the freedom of movement. It is made of acrylonitrile butadiene styrene and fabricated by using a 3D printer. It is stated that the user would need a training period to control the device. Currently she can just play simple pieces [16].

Figure 7. Bow holders already designed; The spatula bow adaptation [15] A). Violin Prosthetic Arm [16] B). Shea's bow holder [17] C). May we help bow holder [18] D). TRS prosthetics; Violin 2. [19] E).

b) "Shea's bow holder". Figure 7 (C) and Figure 8.

E-NABLE community is a global network of volunteers using 3D printing in PLA to help people with upper limb difference. One of its members, Frankie Flood has developed the Shea's bow holder. It was designed for an end-user who was born without fingers on her right hand. This device allows her to hold the bow. The bow is dismantled to attach the bow and no hardware is necessary other than Velcro straps to attach it to her forearm. [17].

Figure 8. Shea's bow holder. [17]

c) "May we help bow holder". Figure 7 (D) and Figure 9.

May we help organization is a made of 150 volunteers from different professional backgrounds helping people with disabilities who are striving to become more independent and/or pursue a passion. The designer of this device is Bill Sand, which has created this simple device to help people missing finger to play the violin. The design consists of one piece attached to the bow frog. From this piece arises an arc-shape-extension that serves to hold the bow with the user's fingers [18].

Figure 9. Feet bow holder. "May we help "organization [18]

d) "TRS. Violin 2". Figure 7 (C).

The TRS prosthetic Violin Bow Adapter 2 consists of a lockable ball and socket component modified to be assemble into a prosthesis. The adapter can be adjusted to any angle to help ensure optimal playing position. The bow is held firmly in place by using screws [19]. Literature was not found about a real case of person using this device, therefore no real feedback from a user was found.

Chapter 1
Analysis phase

The design problem, goals and design assignment are analysed in order to set up an overall direction for the project. In the last part of this chapter, a function analysis will show the basic functions involved for a possible solution.

2 Problem definition

The user wants to play the cello, but she suffers from rare blood vessel anomaly called Capillary lymphatic venous malformations (CLVMs) in her left hand. She wants to play the cello by using the bow with her left hand, contrary as classical players do. She has got two digits with partial movement and sensitivity. She can partially hold the bow but she cannot grip and control the intensity that is normally regulate by the index. Moreover, she is not able to make the necessary counter balance while holding the bow, which is done classically by using the 4th and 5th finger. Figure 10 shows her attempt of using the bow without any extra support.

Figure 10. Photos taken during the first meeting. User's first attempts of holding the bow. Birmingham. 15/02/2019

2.1 Problem statement

The challenge in this thesis is how to fabricate a task specific prosthesis that is affordable, easy to manufacture, body powered, specifically designed for the end-user's disability and accepted from her. Most importantly, the design should take most advantage of her current capabilities and allow her to fulfil the bowing actions required to match the functional capabilities of the classical players.

Specific problems had arisen from the general problem:

- Which are the necessary and specific requirements for the end-user to design a specific bow holder device?
- How can a reliable and comfortable device be designed?
- How can the prototypes and the final device be easy-fabricated?
- What if user's hand dimensions change due to its disease or her own growth?
- How could be hand measurements and proportions be obtained?

3 Stakeholder analysis

Table 2 shows the evaluation and identification of the needs from the different people involve in project.

Table 2. Stakeholder analysis

STAKE HOLDERS	Characteristics, interests and expectations	Potential, resources and capabilities	Deficiencies	Conclusions
USER	She is the specific user from this project. A 7-year-old girl living in Manchester (UK). She has a disability in her left hand due to a lymphatic venous malformation. She has got two digits with partial movement and sensitivity. She is able to hold the bow, but not to correctly grip and control the position.	The user must feel that the device is comfortable and useful to assure a future success and its use. The user is needed to test and evaluate the problems during several times along the product development to improve the concepts and analyse the problems at different stages.	The user lives in another city, 300 km away from PDR. She has never used a bow before.	Information from the user is of main importance. Her opinion about comfortability, usability, aesthetical aspects should be studied and analyse to identify the main requirements and desires for the final product of this project. Measurements and prototypes will be specifically adapted to her hand.
OHMI: RACHEL WOLFFSOHN	A UK-based charity pioneer the development and adaptation of musical instruments for those who are physically disabled.	To enable people to tackles specific challenges, or make their work more widely available. Technical knowledge about positions and requirements while using musical instruments.	Limited resources and access to specialist design and manufacturing equipment that enable them to tackle specific challenges or make their work more widely available.	They are the link between PDR and the user. They are up to help in user trials and all needed information related to task specific instrumental prosthesis.

MIKEL AND FILIPA RISTE	User's family.	They expect the user to be able to use a bow and learn how to play the cello. They have seen User's growing and evolve with her problem, so they can give a useful point of view about her deficiencies and strengths. Furthermore, the user's father is a cellist, he could be helpful with the necessary position in User's hand while bowing.	The user lives in another city, 300 km away from PDR.	They want a comfortable device to wear and easy to use for their daughter. I need them to collaborate with me in the user information and
PDR	PDR is a world leading design consultancy and applied research facility.	Expertise's information when needed. Resources and 3D printers.	Limited amount of resources for the project. (500pounds)	Support and supervision along the project. 3D printers and manufacturing information and tools.
SOCIETY	There are more people with similar problems as User who would love to be able to play a musical instrument.	To allow people with upper limb difference the access of learning music and playing instruments. Disable people are on need of these low-cost activity prostheses.	Resources to continue the study and make it adaptable.	To improve people's life. Social inclusion

4 Goals

Previously the problems were identified, and the involved stakeholders were described. During this section, the goals of the project will be defined. These goals are divided into the main goal and the sub-goals.

The main goal is:

"To create a specific design of a cello bow holder device for a 7-year-old girl with a left-hand disability."

Which includes to create a comfortable, low-cost and easy to use bow holder body-powered prosthesis that will allow the user to match or supersede functional capability of their peers. Furtheremore, the device must help her to be able to reproduce necessary movements involved in bowing.

The main goal is complemented by the following sub-goals:

- To define a list of general and specific requirements to guide design process which the final bow holder device should fulfil.
- To find the best way of fabricating the prototypes and the final design.
- To create an adaptable device for her own growth.
- To work toward the ambition of an open source and modifiable design to ensure others with similar difficulties to adapt the device for their specific needs.

Figures 11 shows in first place the problems cause-effect diagram and secondly the goals cause-effect diagram which will result with the user and her family satisfaction.

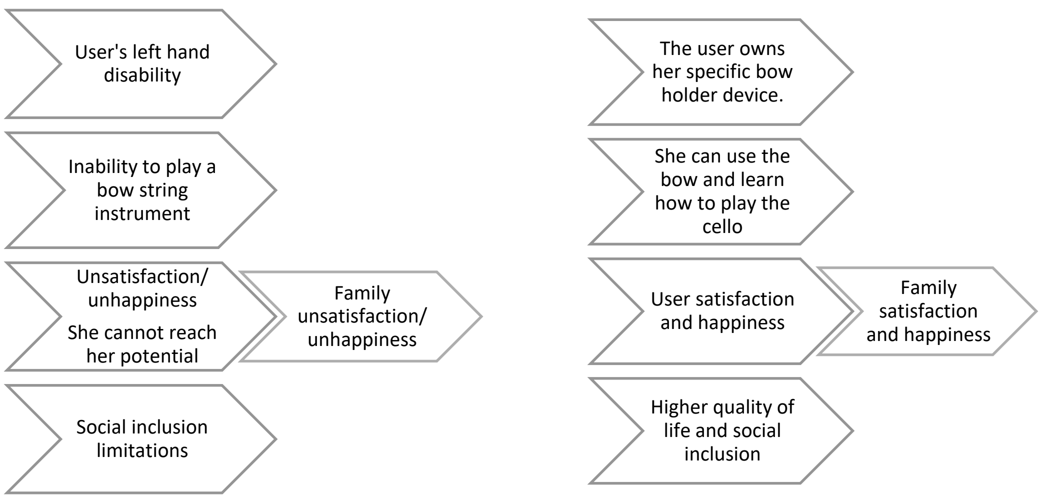


Figure 11. Cause-Effect problems diagram. Cause-Effect goals diagram.

5 Design approach

A human-centred design methodology has been chosen as a creative approach to problem solving during this project. The user opinion has been considered from the beginning of the design process and her capabilities and limitations were evaluated across a variety of methods, with the objective of producing a safe, efficient and satisfying solution [20]. Therefore, a combination of observational methods and user trials were used to develop customized and technical specifications.

Design and production technologies available through PDR were used to design and produce the bow holder prototypes. This will be complemented by parametric technical and free form design by Fusion 360 and manufacturing methods such as 3D printing in flexible and hard polymers.

The goals can be achieved by two possible design assignments:

- **First, to design a bow attachment, leaving the user's limb free.**
- **Second, to design a bow holder attached to the bow and to the user's hand.**

Both are non-invasive approaches designed for a specific user.

5.1 Demarcations

The solution will be technical and will be restrict by several demarcations that will limit the amount of feasible solutions. The most important limitations are time and money. Only six months and a modest budget are available for developing the solution. This means that it is impossible to, for instance, develop a design based on relatively new and/or very complicated theories in physics or develop a solution that relies on complicated manufacturing processes. Moreover, to effectively meet the needs of the end user it is required a customization and modification over a longer time [21]. Moreover, this project needs several user tests and interactions to create the desired device. Considering that this project last 6 months and the end user and her family are based 300 km from PDR, the project will be difficult to obtain accurate measurements and obtain information about the hand's dimensions considering that the user's location restricts the total number of meetings and evaluations of her hand.

6 Function Analysis

A funcitonal analysis of each design approach is explained belowed.

6.1 Bow holder attached to the bow, leaving the user's limb free.

The main function of the device is to allow the user to use and control the bow.

- Body movement- MATERIAL TRANSPORT
- Connection between the limb and the bow. Force and motion transference from the forearm/wrist to the bow- ENERGY TRANSPORTATION
- Bow attachment- MATERIAL CONNECTION
- Bow movement- MATERIAL TRANSPORT

Figure 12. A function block scheme of a bow adapter

6.2 Bow-holder hand specific prosthesis

The main function of the device is to allow the user to use and control the bow.

- Body movement- MATERIAL TRANSPORT
- Device connection to the user- MATERIAL CONNECTION
- Transfer force and movement from the forearm/wrist to the device- ENERGY TRANSPORTATION
- Device connection to the bow- MATERIAL CONECTION
- Bow movement- MATERIAL TRANSPORT

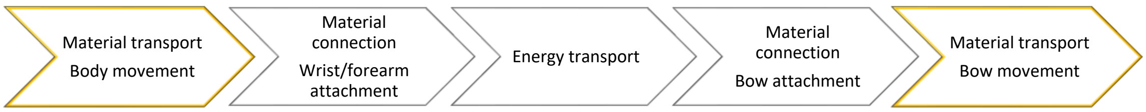


Figure 13. A function block scheme of a prosthetic bow holder

Chapter 2.
Design criteria.
Requirements and wishes

Once the goal and the design assignment have been established, the next step is to create a list of requirements that the solution must satisfy and a list of wishes the design might fulfil.

The design criteria are divided in two phases; *general requirements* and *specific requirements*. The first one is born from literature regarding with task specific prosthesis, previous bow holder's analysis, biomechanical research on bow string instruments and 3D printing. From this literature review and meetings with different experts, a general list of requirements and wishes was created to set a list of safe and reliable specifications for the general layout of the device. Additionally, other characteristics such as aesthetics and project limitations were also considered in the *general requirements* [22]. While developing the first phase of the design criteria, it was important to restrict enough the requirements and wishes, but to not make excessive assumptions before having real tests directly with the user. The second phase has given rise to the *specific requirements and wishes*. Specific features and necessities from the device were result from the User trial (*For further information See Chapter 4*).

1. General requirements

Since not enough or relevant studies regarding to bow holder devices have been found. Other studies related with hand requirements and hand task specific prosthesis were used instead. Adaptive devices control, cosmetics and comfortability are the main aspects to take into consideration when designing a prosthesis or hand specific device [23]. As stated by Biddiss (2007), "*the lack of functional gain, discomfort and more sensory feedback without the prosthesis are the main reasons for user rejection*" [24].

1.1 **Comfortability**

The increase of comfort consequently increases the compliance of usage, rising the potential acceptance of the device [24]. It is of main importance that the material in contact with the limb has a good shape and it is made of a comfortable material to the skin. The device must allow the hand to feel the bow natural in the hand. Consequently, the prosthesis must have the correct weight. Due to the adaptive device is external to the body, it will feel heavier even if the weight is the same as a human hand. The bow holder must have a weight lower than the user's hand (which is about 0,5% of her total weight) which are around 100 g for a 7-year-old girl [25]. Furthermore, to have a good shape, it must fit in the user's hand. The device must not be longer than the user's hand and it must be closer to the bow as possible, allowing her to hold the bow by herself.

1.2 **Function/Control**

Device control and functionality will increase the acceptance of the device by the user [26]. The prosthetic must help the user to reproduce in the most accurate way as possible the actions necessary for bowing: which means the prosthetic must help the user to glide the bow correctly over the strings and to move the bow from tip to frog with equal weight [27]. Additionally, it must allow the transfer of motion from the user's body to the bow. It must allow to control the pressure onto the strings from the arm weight into the string while bowing [28].

1.3 **Mechanical Requirements**

a) It must be a body powered device. In this case, the actuator responsible for moving and controlling the bow holder and accordingly the bow is the user's body. Muscles are on charge of the mechanical work while the tendons give the elastic energy reserves [29]. Movement intensity, control and the correspondent feedback are provided by the central nervous system [30].

b) The minimum force applied downward to a string (force orthogonal to a string) is the bow weight which averagely is 60 grams (0,59 N). Figure 14 shows the bow position and down force graphs while bowing a violin. It is taken as a reference force applied downward the following range 0.59–4.0N [31].

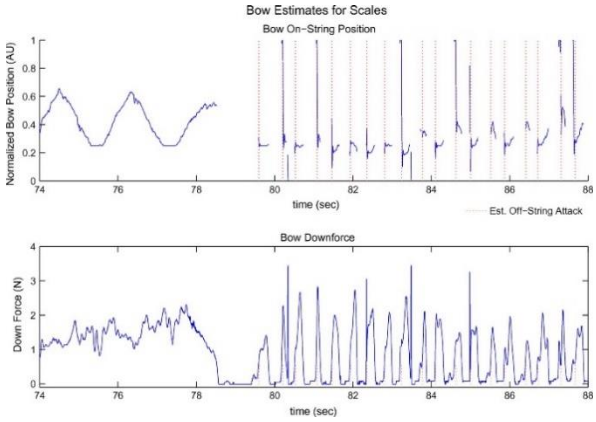


Figure 14.Bow position/Down forces [31]

c) The bow attachment must be well connected to the bow to not loose energy needed to bow [32].

1.4 **Materials and Manufacturing methods**

Due to our limitations in money and time our design must be low-cost and easy to manufacture. Because of that, the main manufacturing method used in this project is Fused Deposition Modelling (FDM). In FDM a polymeric filament is heated and pushed through a nozzle to build the prototype layer by layer. The materials used are thermoplastic polymers in a filament form. FDM Technology works with specialized 3D printers [33].

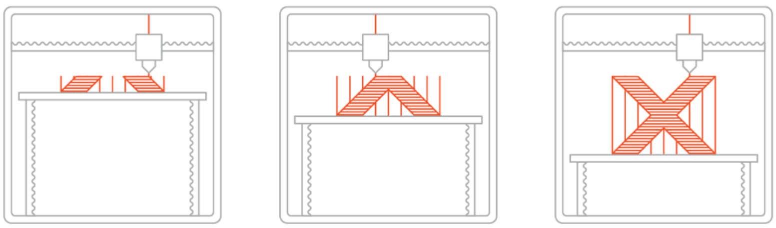


Figure 15. "3D HUBS". 3D printing process [33]

1.4.1 3D printing requirements

It is important to take into consideration when printing in FDM that is not very good for precise details and it is necessary to avoid large flat surfaces and use rounded corners to avoid warping. In the following Figures 16 and 17 show the main 3D printing rules for FDM to have under consideration for a good result in the FDM 3D printed components [33].

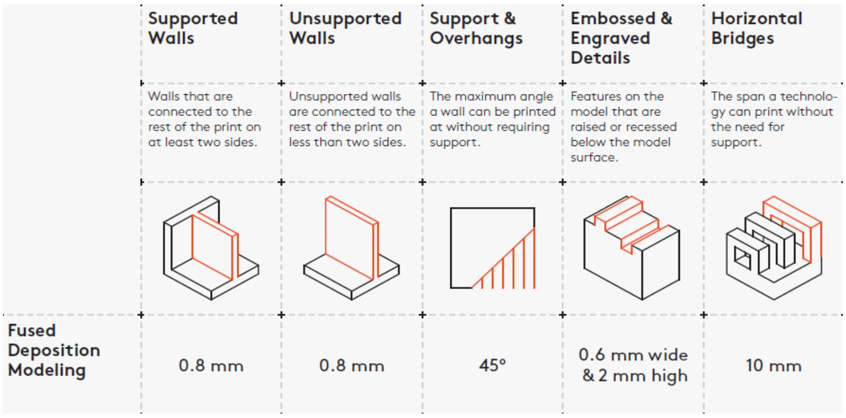


Figure 16. FDM 3D printing rules 1. [33]

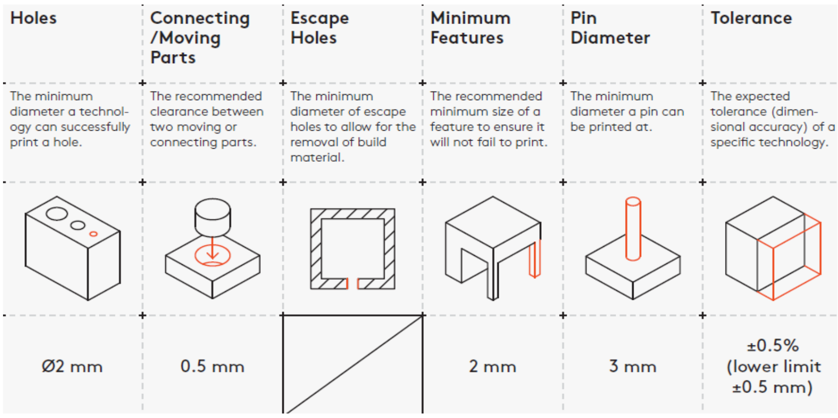


Figure 17. FDM 3D printing rules 2. [33]

1.4.2 Materials requirements

They must be low cost and biocompatible with the skin.

1.5 **Safety**

The prosthesis should be safe to use which includes, to not use toxic materials, to not produce rashes or other negative body reactions, to not cause injuries or pain to any part of the user's body.

1.6 **Practical considerations**

The prosthesis must be accepted and liked by the user. Colour, texture, symmetry and proportions of a product design give meaning and enjoinment to the users. If the user is pleased by the aesthetics of the device, the probabilities of its use will increase. In the same way, an easy to use device, intuitive and with simple assemblies will encourage the task specific prosthesis acceptance [32].

1.6.1 Easy to use

An easy to use device is defined by an easy assembly mechanism, requiring less than 15 minutes assembly time.

2 General wishes

Bow holder Location. Sarah Day, a fellow teacher in the department of bioengineering's national centre for prosthetics and orthotics from the University of Strathclyde, has recommended to locate the device in the most comfortable place of the user's hand and to place the material connection with the user's body in the area where the user has less range of usability. People with upper limb disabilities feel more comfortable leaving free the "non-problematic areas". In our case, leaving the wrist free it would be a not necessary but good characteristic to accomplish.

3 Specific user requirements and wishes

A combination of observational methods and a user trial were used to develop the specific user requirements and wishes.

3.1 Specific user requirements

7 Hand position

- Hand as close to the bow as possible, which means to reduce height and distance from the bow holder to the bow as possible.
- The device must correct the hand position. The wrist must be parallel to the bow stick.
- The device must increase the thumb possibilities related with bowing.

8 Mechanical requirements

- The device must be motionless. In this way, it will help the user to control the device.

3.2 Specific user wishes

- Adjustability. The user can grow, and therefore the necessities can be altered. To compensate this, the prototype should be made such that the behaviour can be altered. This could be done by a modular system easy to make changes to the distances and relationships between the parts.
- The user prefers 2 individual points of support.
- The material connection with the user's skin should be made of TPE or a flexible material in contact with her skin.
- The bow holder should have plane surface in contact with the palm of her skin.

4 Summary requirements and wishes

General Requirements

Comfort

-It must allow a comfortable and good fit for her hand.

- It must be weight less than 100 g.

Control

-It must allow the user to hold the bow.

-It must reproduce the movements necessary for bowing:

- To glide the bow correctly over the strings.
- To move the bow from tip to frog with equal weight.
- To transfer motion onto the bow.
- To control the pressure used on the strings while bowing.

Mechanical Requirements

-It must be a body-powered device.

-It should stand a downward force of 4 N.

- The bow attachment must be well connected to the bow.

Materials and Manufacturing methods

-It must be low cost produced.

-It must be easy to manufacture.

-CAD designs must follow the FDM designing rules (If they are created to be 3D printed)

-It must be well connected/fasten to the bow.

Safety

-It must be made of biocompatible materials in contact with the skin.

-It must not produce rashes or negative body reactions.

Practical considerations

-It must be aesthetically accepted by the user.

-It must be easy to use. (Less than 15 min of assembly).

General wishes

-The bow holder should be placed in the area where the user has less range of usability.

Specific requirements

Hand position

- Hand as close to the bow as possible.
- The device must correct the hand position. The wrist must be parallel to the bow stick.
- It must increase the thumb possibilities.

Specific wishes

-It would be preferably made modular and adjustable.

-It would preferably have 2 points of support.

-It should be manufacture of TPE or a flexible material these parts in contact with her skin.

-The surface in contact with her hand palm should be preferably designed with a plane surface.

Chapter 3. Synthesis I

The objective of the Synthesis I phase was to develop diverse prototypes to test with the user in order to obtain a deeper understanding of the requirements and practices needed to develop a reliable and functional task specific prosthetic device. The motivation was to explore the potential of 3D printing and other rapid prototyping technology for designing customized bow holders specifically adapted to the user.

During this phase, a lot of ideas are generated, selected, developed and finally manufactured. The phase consists of the following sub-phases:

- *Brainstorm: research and idea generation.*
- *Pre-concepts: The best ideas are further developed and become pre-concepts.*
- *Concept creation: different concepts were created to represent very diverse ideas.*
- *Manufacturing process: building the physical prototypes by using 3D printing and rapid prototyping.*

1 Brainstorm

To develop a deeper understanding of the requirements and practices needed for developing a reliable and functional task specific prosthetic device, different concepts had to be tested with the user. For this reason, different low fidelity bow holder' prototypes were created. In the design process, the first step was to look for ideas and consequently to create a mind map.

1.1 Searching for ideas

Before brainstorming, other adaptable devices for specific activities, mechanisms and previous bow holders were studied (further information in the *literature review*). Figure 18 shows three different cases of adaptation to an oar, each one adapted to different cases of upper limb disabilities. This activity was especially useful due to its similarities with bowing. For instance, both need gripping and holding actions of a stick. In picture A, we can observe the *Hand adaptation* tool. This hand grip is made for those who have some hand function and can grip the paddle shaft on their own, but they need a bit of help for it. In the second two pictures, B, we can observe the *Wrist adaptation*, which is developed for those who cannot grasp the paddle shaft. It is made of two components, the wristband and the paddle attachment. This mechanism allows power transmission, rotation and control without releasing. Finally, in the C image, we can observe the *Paddle Pivot* mechanism which was created for people with a missing arm [34].

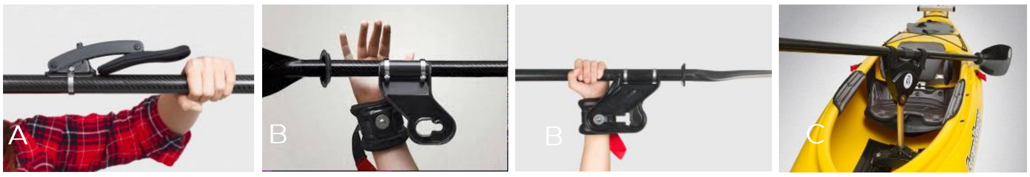


Figure 18. A) Hand adaptation B) Wrist adaptation C) Paddle pivot [34]

In addition, daily life observations of common devices attachments and mechanisms, from bikes to desk lamps, were also briefly analysed. Finally, already existing accessory devices to control the bowing were researched. Figure 19 shows devices to help some novel string instrument players when they are starting to bow.

Figure 19. Accessories to help in bowing [35]

1.2 Ideas generation

In order to solve the design assignments, the problem was approached in a modular way, separating work into simple aspects by using the functional analysis already described in the analysis phase. Instead of trying to solve the problem in one, a brainstorm focussing on 3 different aspects was performed: material connection 1 (body attachment), material connection 2 (bow attachment) and energy transport (mechanism to join both material connections (1,2)).

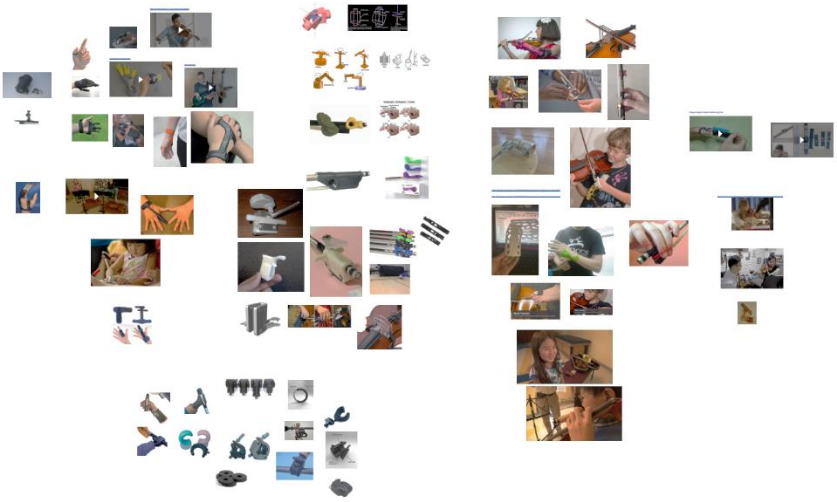
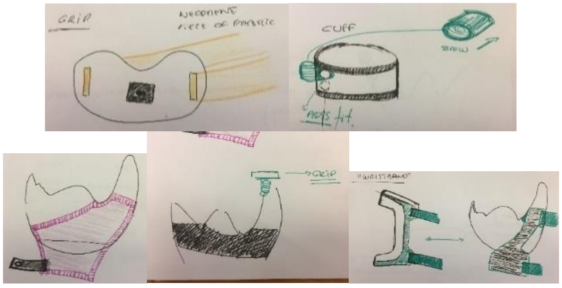
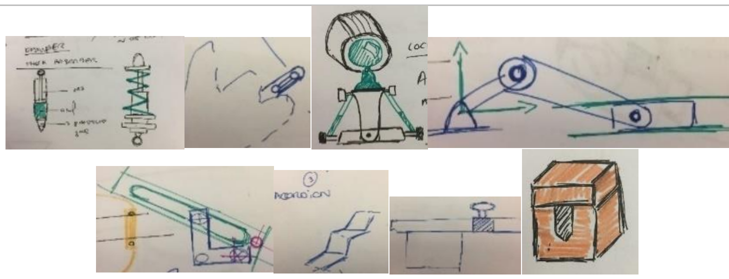
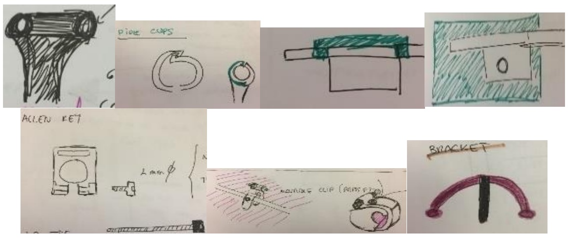


Figure 20. Synthesis I. Brainstorm map

At this stage, it was not known which alternatives were going to match with the user or succeed in the project, therefore the more ideas the more possibilities. I wanted to try as many options as possible. Due to money and time restrictions, it was not worth spending too much time in a very complicated or expensive alternative, without knowing it will have a certain future. The objective was to create and realise physical objects and try them with the user. The more different options I could try, the more specifications I could obtain. On other hand, the ideas had to have a clear purpose and they should be easy to manufacture. Moreover, it was considered useless to test two concepts expressing similar ideas. For example, an accordion mechanism and a spring both represent a translational movement, so it is not worth spending time and money on both.

Once I had enough material, I started to sketch up different pre-concepts or solutions grouping them by a functional classification as Table 3 shows.

Table 3. Sketching ideas

Material connection (with her body)	
Energy transport	
Material connection (with the bow)	

2 From ideas to pre-concepts

The rough prototypes were in a premature stage of development and the design criteria was still not fully described. To create concepts, the following requirements were considered:

R1: Low-cost production

R2: Rapid prototyping and easy to manufacture

R2: Functional. Reliable enough to withstand the activities develop in the trial.

R3: Safe for the user

R4: Potential. Each prototype should test a specific and different idea.

R5: Hand/bow dimension

A modular design method was chosen. It allows to adjust parameters in one design session rather than requiring multiple, which game the opportunity of accelerating the design process and in addition obtaining measurements that would be easier to incorporate into parameterized 3D models [21]. For this reason, pre-concepts were already conceived in a modular way. Figure 21 shows the creation-process of some of the pre-concepts. The first sketch on the top left is a flexible glove with an attachment to the bow, the one on the top right is a bow attachment assembly to a modelling clay piece, and finally the one at the bottom is a rotator bow attachment control is provided by a bracket held by the bow and the whole mechanism is attached to the hand by a grip.

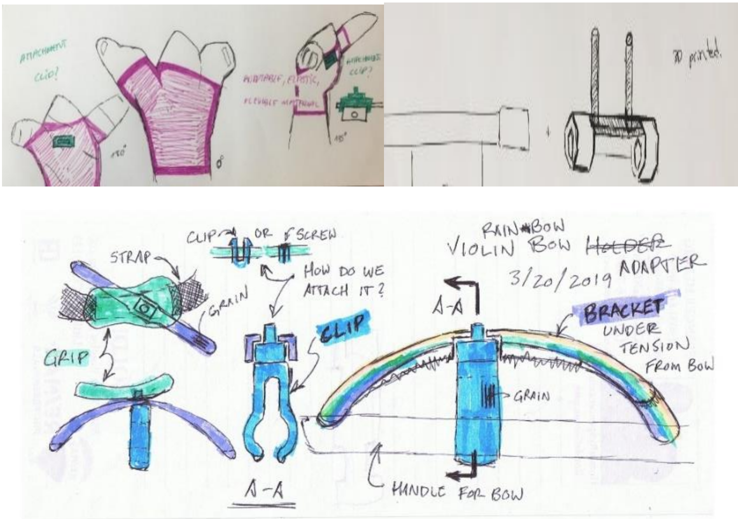


Figure 21. Synthesis I. Bow holder sketches

2.1 **Pre-concepts**

Pre-concepts were created and represented in sketches and CAD (Fusion 360).

2.2 **Material connection. Hand attachment components**

HA1. Round grip

It is made of a semiflexible material. Figure 22 shows its shape. This component is attached to the user’s hand by a piece of fabric band glued at the end to a Velcro strap or by a latex free tourniquet by using a buckle attached to the component through two curved holes at each side of the piece. The aim of them is to have an adaptable tightness to the limb. The round grip can be mirrored, which means that the side in contact with the hand could be either the big round surface, or the opposite face. It has a circular hole in the middle to insert a M4 screw and there are four other small prismatic holes, two at each end of the ellipse. All of them are assembly holes - the one in the centre to screw the component to another module and the four small posts to fix the component by a fit clip to another module.

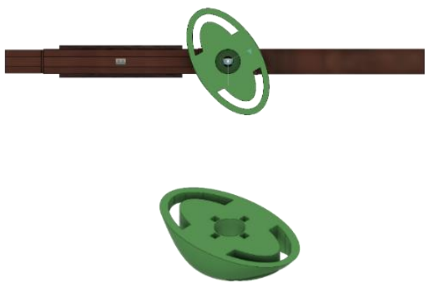


Figure 22. HA1 Round Grip. Hand attachment. Pre-concept 1

Ideas to be tested:

- Best location to locate the hand attachment.
- HA1 can be located easily at different locations in the hand.
- Comfortability; test of different surfaces.
- Functionality; different assembly mechanisms.
- Height of 12,5 mm. (width)

HA2. Rectangular grip

It is made of a semiflexible material, to adapt to the user's hand surface. This hand attachment has a rectangular shape with two long holes at each side to insert the fabric band or the latex tourniquet using the same mechanism explained for HA1. Hem. Figure 23 shows its shape and the holes arrangement. It has an M4 hole to screw this component to a rigid red cubic component. These two components can be tight to each other at different degrees, controlling their mobility and orientation with respect to one another.

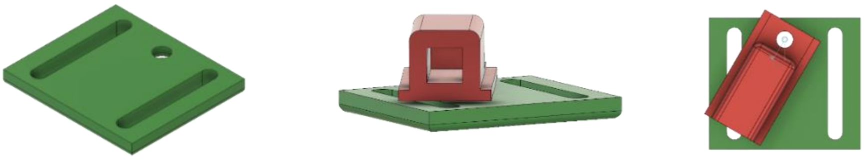


Figure 23. H22 Rectangular Grip. Hand attachment. Pre-concept 2.

Idea to be tested:

- Best location to locate the hand attachment.
- Output angle. Angle measurements from the grip to the component which goes into the bow.
- Height of 4 mm. (width)

HA3. Modelling clay

Clay is thought as a good option because of its reproducibility and free hand adaptation. Moreover, it will encourage the user to modify the prototype and increase her participation in the design process. The clay is used to mould grip of the user's hand. Once the desired shape is defined, by baking it at 110ºC for 20 minutes, we could obtain a solid mould, avoiding the risk of shape deformation after its use.

Figure 24. Modelling clay. Hand attachment. Pre-concept 2

Idea to be tested:

- To get an imprint of the hand while holding the bow.
- To easily try new concepts during the user trial.

2.3 Material connection. Bow attachment components

BA1. Nut/screw clamps

Clamp system with a pair nuts/screws system to allow variation in its tightness and fixation to the bow. It gives a point of support for the bow holder and a connection to the bow. A nut is incorporated inside of the structure as shown in Figure 25 It is made of a rigid and friction resistant material to withstand the rotation friction given to the attached components joined to the top by the screw and the torsion while it is tightly connected to the bow.

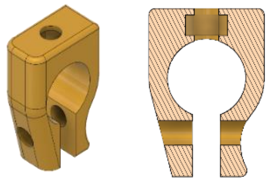


Figure 25. BA1 Clamps. Bow attachment. Pre-concept 4.

Idea to be tested:

- Location of the bow holder along the bow stick.
- Assembly mechanisms reliability.
- Material/shape reliability.
- One or more clamp supports can be tested to evaluate different support points.

BA2. Attachment to the frog

Rigid attachment to the bow which provides a perfect fit to the the frog. It is made of a rigid material.

Figure 26. BA2 Frog attachment. Bow attachment. Pre-concept 6.

Idea to be tested:

- Assembly mechanisms reliability.

2.4 Energy transport (mechanisms to connect both materials attachments)

E1. Object to fit the clay into the bow.

Simple mechanism to attach the clay to the bow attachment. It is made of a rigid material.

Figure 27. E1 Object to fit the clay into the bow. Pre-concept 7.

Idea to test:

- To give support to the clay.

E2. Bracket components

Intermediate mechanism between the bow attachment component and the grip. The objective of this module is to allow a band to go through the longitudinal holes one at the end of the rectangle that you can see in Figure 28. This band or "bracket" I also connect to the bow form one or two of the sides. In Table 5 a better explanation is given about the bracket. The bracket should be mirrored so it lines up for bowing. Each end of the bracket will be held under tension on to the bow's handle by the assembly in the middle. Also, four other small prismatic posts are placed in this module to use them in the grip assembly.

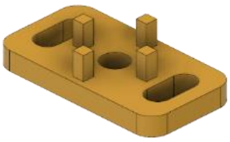


Figure 28. E2. Bracket connector. Pre-concept 8

Idea to test:

- Extra-feedback in the rotator mechanisms.
- Reliability of assemblies.
- Rotator mechanisms.

E3. Lego mechanisms

E3 is thought to be combination of Lego assemblies to iteratively adjust the length and DOF between the hand attachment and cello bow holder. Lego experimentation led her to provide direction about the comfort of his prosthetic and to make concrete suggestions to researchers regarding the addition or removal of Lego layers. Specific dimensions for hand her hand the bow. Figure 29 shows the Lego components.

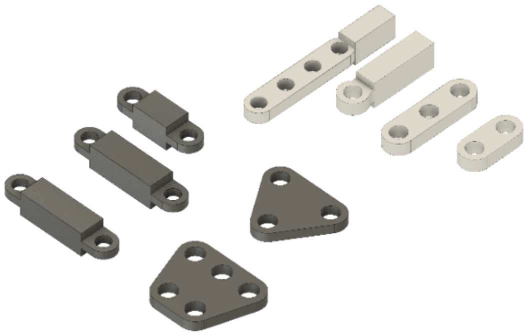


Figure 29. E3. Bracket connector. Lego Pre-concept 9.

Idea to test:

- Length form the grip to the bow evaluation.
- Different motions and degrees of freedom.

E4. Cubic fit clip attachment

Connector between the HA2 rectangular grip and the bow attachment. It gives the control in mobility and orientation from HA2 to itself. Figure 30 shows the cubic connector.

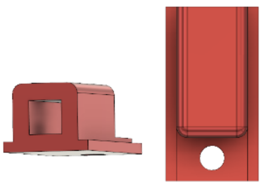


Figure 30.E4. Cubic connector. Lego Pre-concept 10

Idea to be tested:

- Output angle. Angle measurements from the grip to the component which goes into the bow.
- Assemblies mechanisms.

3 Combination of the pre-concepts. Prototypes definition

In the previous section 9 pre-concepts were created from the idea generation. Finally, 7 final concepts have been developed by joining different pre-concepts in a different way.

Table 4. Prototype description. Synthesis I. P1

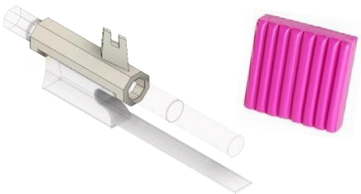
REF	PRE-CONCEPTS COMBINATION	NAME	DESCRIPTION	FINAL CAD MODEL
P1	**HA3+BA1+E1**	**Prototype 1. Rigid prototype**	The bow holder is fixed to the bow at the frog. The clay is moulded in a cylindrical shape and attached to the bow holder top by squeezing it against the top object. The user carefully should try to hold the bow and squeeze the clay creating a specific grip on the bow holder. Finally, the clay is removed and introduced in the oven at 110ºC. After 20 min we will have a rigid specific grip for the user.	

Table 5. Prototype description. Synthesis I. P2, P3, P4.

REF	PRE-CONCEPTS COMBINATION	NAME	DESCRIPTION	FINAL CAD MODEL
P2	**HA1+BA1**	**Prototype 2. One point of rotation**	By a screw the grip will be connected to the clamp which will be still, without movement, in a specific place on the bow. It would be ideal to add stops to the angle of movement, so it stays within a nice range for bowing.	

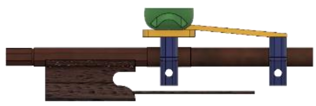
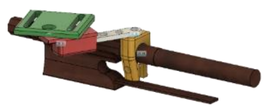
P3	**2*HA1+E2BA1**	**Prototype 3. 2 points of support**	A bracket connection will be added to P2 giving extra support, control and feedback to the main rotator component. The screw in the second clamp should be completely tight. The bracket will be held under tension	
P4	**3*HA1+E2+BA1**	**Prototype 4. 3 points of support.**	An extra support point is given to P3. 2 extra support points (clamps) are joined to the main component by a bracket. The screw in the second and third clamps should be completely tight. The bracket will be held under tension	

Table 6. Prototype description. Synthesis I. P5, P6, P7

REF	PRE-CONCEPTS COMBINATION	NAME	DESCRIPTION	FINAL CAD MODEL
P5	HA2+E4+BA1	**Prototype 5. Lego stationary longitudinal length**	Length evaluation. By using 3 different holes separated form each other 1 cm, the best length from the grip to the bow will be evaluated. The lego component will be joined to the grip by a fit clip from one of the ends and the red cubic component and it assembly to the clamp by a screw throught one of the holes.	
P6	HA2+ E4+BA1	**Prototype 6. Lego degrees of freedom DOF**	Rotations and DOF evaluation. The first lego component will be joined to the grip by a fit clip from one of the ends to the red cubic	

			component. The second lego component is assemplied to the first lego through and attached to the clamp through a screw. By tightening the screws at the joints we could control the movement in the joints. From not having movement and defining a rigid angle to allowed rotation and adding a degree of freedom to the joint.	
P7	HA2+ E4+BA1	**Prototype 7. Translational movement.**	Translational movement evaluation. By using different Lego using 3 Lego components we define a square mechanism with movements at 2 joints. Rigid to the attachment to the clamp and to the grip. Motion in the 2 lateral joints creating an accordion translational mechanism between the grip and the clamp.	

4 Summary of ideas to be tested with the prototypes

I1. What is the best location for the hand attachment?

I2. Which is the ideal height or distance from the user's body to the bow?

I3. Which is the best angle between the hand attachment and the bow attachment? Which is the most suitable distance?

I4. What is the best location to attach the bow holder?

I5. How many support points work better for the user? Which is the best distance between them?

I6. Is it better a motion or a motionless bow holder? Which kind of motion mechanism would work better?

I7. To obtain an imprint of the hand while holding the bow.

I8. To create new concepts with the clay to obtain new ideas.

I9. To evaluate the best assembly mechanism. Which is the easiest to use?

I10. To evaluate the most comfortable surface.

I11. Which are the most valuable prototypes?

5 Prototype production and material selection

5.1 Rapid prototyping and manufacturing methods

In parallel to the idea generation, different materials for rapid prototyping and 3D printing were studied. The main selected manufacturing process was fused deposition modelling a type of adding manufacturing technology. A summary of the FDM materials selected and its properties can be found in the *Appendix A.* Furthermore, other materials easy to obtain and use were applied in the manufacturing process such as modelling clay, diverse kind of fabrics, Velcro, glue, Kinstuglue, nuts, screws, etc…

5.2 Material selection and layer orientation

Each component was thought to have a different function. Different materials brought the opportunity to fulfil different characteristics. Some components are thought to suffer from more stresses and frictions, for instance, the attachments and components involved in motion mechanisms. These ones were printed on Nylon or PLA which are rigid materials, Nylon stands the friction better than PLA, but it is slightly more expensive. On the other hand, other components are required to stand slight bending stresses but without being easily deformed. These ones were made of PLA flex. Finally, these components in contact with the user's body part were needed to be flexible, adaptable to the user's skin and comfortable. The material selected was TPE. Figure 31 shows three examples: In Figure A there are two grips made of PLAflex, in Figure B a rotator clamp is made of Nylon and finally in Figure C a wrist band was printed in TPE.

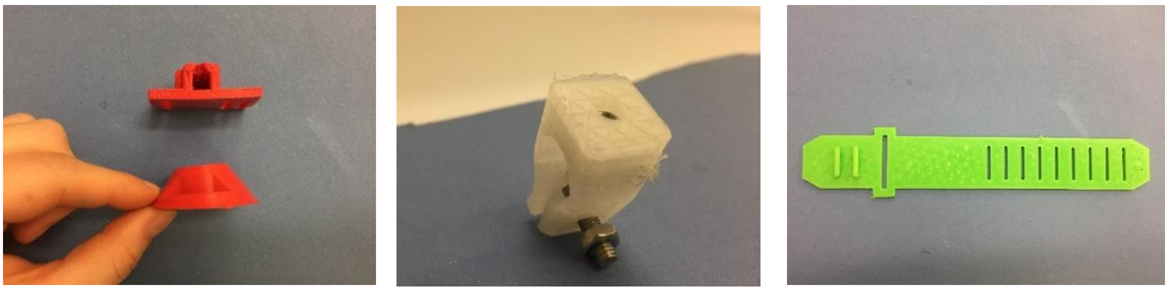


Figure 31. Synthesis I. Material selection. PLA flex picture A. Nylon picture B. TPE picture C.

Furthermore, the build orientation of each component had to be considered. Each component must be printed in such a way that they would lie on the side to minimize the amount of support material and in a way that the component will stand better stresses and forces. For example, a same 3D printed object could be much stronger in the XY direction than the Z direction. Figure 32 shows an example of the layer orientation and the applied forces in the structure. Figure 33 shows a real example of the layer orientation of two of the Nylon components.

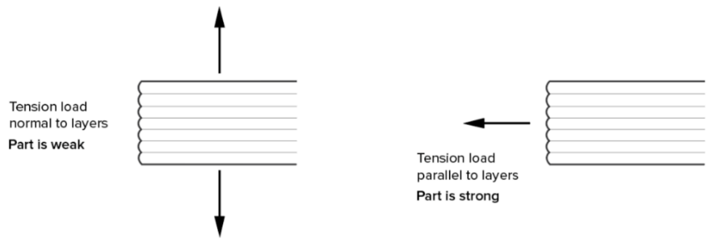


Figure 32. 3D hubs. Layer orientation (FDM)

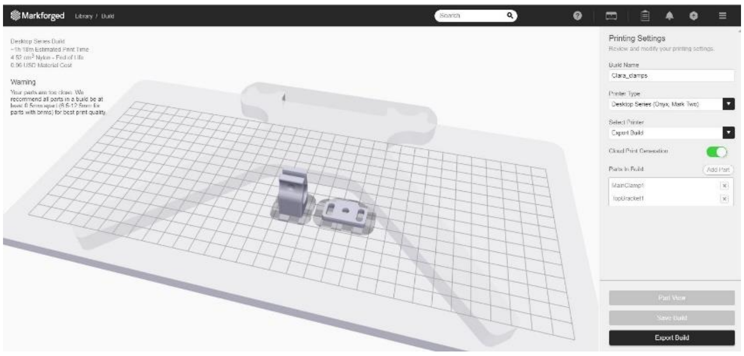


Figure 33. Synthesis I. Eiger software. 3D printing software settings and disposition of the Nylon components lying in its best side to minimized supportive structures and withstand the necessary forces.

5.3 3D printing process description

The specialized FDM 3D printers used along this project were a Markforged 3D printer, used to print the Nylon components, a Wanhao Duplicator i4 and a Ultimaker machines to print the PLA components and a Wanhao duplicator i3 with a diabase flexion extruder modification to print the TPU and PLA flex components. Markforged uses its own cloud base software, Eiger, while the other 3D printing machines use Makerbot desktop software to prepare the 3D printing settings.

From the CAD software (Fusion 360 in this case) each component was exported to their corresponding .stl file format. All pieces to be fabricated with the same material and same settings were opened in the same file. For instance, in Figure 33 the Nylon components are shown in Eiger were they were chosen the desired printing properties. Both software, Eiger and Makerbot, automatically generate the necessary support material according to the type of components and their shapes. Once the settings were ready, a g. code file is created and saved on a usb-stick. The usb-stick is inserted in the corresponding 3D printer and the start bottom is clicked to start the printing process. It is important before starting the printing process to slightly glue the building plate, so the 3D printer components do not move while the

3D printing process occurs. To obtain good 3D printing results it is needed that the pieces stay fix to the plate. The printing time varies based on the amount of material to print, which is determined by the number of layers and the density of these layers. The least density, the more details and more printing time is needed. Figure 34 shows the printing process of part of the PLA components and their final assembly by using M4 screws and its corresponding nuts.

Figure 34. Synthesis I. PLA prototypes building process.

Chapter 4. User Trial

As each person and each disability are different each case should be studied carefully. Therefore, it is of main importance to evaluate and consider the user's opinion in the designing process by meetings, interviews, observations and product usability evaluations [36].

After Synthesis I, the next stage was to check which ideas or concepts were appropriate and more valued by the end user. A user trial was carried out to test the different prototypes. The end user was required to try and give feedback of several prototypes and develop a few activities to get a better idea of her current movement possibilities.

- *Introduction*
- *Methods*
- *User trial experience*
- *Specific requirements*
- *Conclusion*

Privacy issues were handled in advance.

1 Introduction

In this chapter, the description of the *User trial* is developed. The goal is to explore the user's influential variables, opinions and perspectives by interviews, user observations and context mapping evaluations. Moreover, a product usability evaluation with low fidelity prototypes was developed to generate specific requirements to guarantee the effectiveness and the goal fulfilment of further bow holder designs. Additionally, this trial was developed to find useful issues and possible enhancements to be considered in future stages of this project [32] [36]. Finally, a Plaster of Paris hand casting of the user's left hand was developed during the trial. This experience will be better explained in the next chapter. At the end of this chapter a unique description of the problem and its results are summarized.

Down below, further explanations of the different methods applied during the trial are explained.

1.1 Discovering insights and creating understanding: Interviews, observations and Context-mapping including a prototype usability evaluation.

Interviews were useful for understanding the user and her parents' ideas, wishes and expectations. Participants enlarged the understanding of the problems and pointed out the strengths of the user condition. Nevertheless, interviews were not enough to obtain a deep understanding of the user experience. Figure 35 shows a scheme which defines three different methods to get to know the user's opinion at different levels. Therefore, other approaches, such as context-mapping and observations were applied to get a deeper insight and understanding [36].

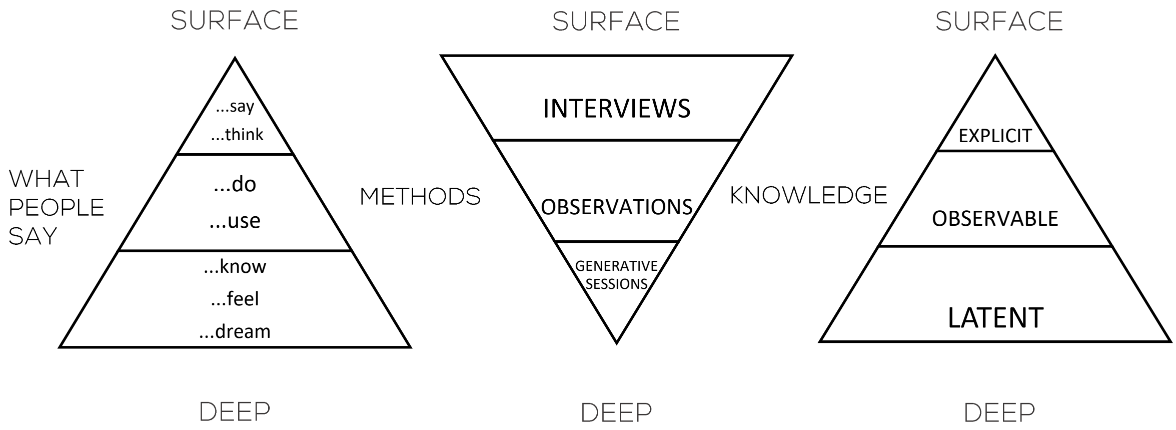


Figure 35. After Sleeswijk et al.,2005

Observations allowed us to understand phenomena and influential variables in "real life cases" by keeping track of the experience and writing down user's comments and impressions during the whole trial. It was important to have a non-judging attitude when taking notes, to not influence the user's and her family members' remarks. Their responses and reactions permitted us to find issues that the participant might encounter while developing an activity and trying the prototypes [36].

Lastly, a context mapping method, "a user centre design approach that involves the user as the 'expert on his or her experience'", was applied during this session. The term "context" is defined as the situation in which a product or service is used, in this case the situation was the user simulating the position while playing the cello and using her own cello bow. The term map indicates that the assimilated information should work as a guiding map for the design, to recognise barriers and opportunities. In addition, through a prototype usability evaluation, assumptions taken in Synthesis I were evaluated.

After the UT session, all the outcomes were analysed to find patterns and possible directions for further designs.

2 Methods

After having prepared the ideas and prototypes, the User trial was organized with the end-user, her parents and Rachel Wolffsohn, the head of the OHMI charity, in Manchester. The meeting lasted four and a half hours. Various activities were included to identify the user's greatest needs for bowing. With the aim of getting deep understanding from the trial the strategies explained in the introduction were applied. The whole session was recorded (voice, photos) and important notes were taken by an impartial third person.

2.1 Interviews, user observations and movement analysis

Technical questions about the user, such as medical information and sensitive information were asked to her parents through a questionnaire available in the Appendix C. Other general questions, easier to be answered by a child were asked to the user, such as favourite colours, preferences and activities.

A general observation was done to evaluate her range of motion, strength and coordination by observations and interactions with the user. To understand the user's perspective modelling clay was used as a generative tool to translate the participants' ideas into desirable solutions. Furthermore, with the aim of testing her wrist mobility she was asked to repeat similar patterns to the ones describe in Figure 36.

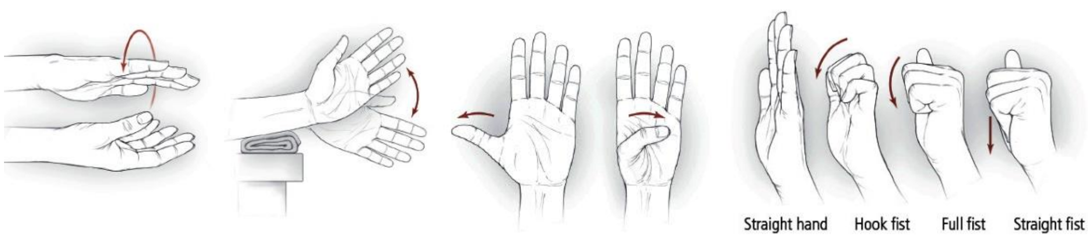


Figure 36. User trial. Hand movement evaluation.

In addition, it was also observed her natural reaction, her interactions and mechanisms to hold it.

2.2 Product usability evaluation

Prototypes developed in Synthesis I were tested with the end-user. Prototypes and materials were assembled and ready to go before starting the trial. Moreover, at the beginning of the session, it was pointed out that the participants could stop the activity at any moment if desired.

The following activities were developed based on the ideas described in Synthesis I.

I1. What is the best location for the hand attachment?

To evaluate the most suitable location to attach the bow holder to the hand HA1 and HA2 components were used. Figure 37 shows these two components. They are easy to place at different hand parts by using an elastic band with Velcro at its ends that goes through the buckles, providing an easy mechanism to modify the tightness and location of the grips.

Figure 37. HA1 and HA2 were used to evaluate the best location of bow holder attachment to the user's hand.

I2. Which is the ideal height or distance from the user's body to the bow?

To identify the best height from the hand to the bow, observations were made while the user was trying all prototypes. Figure 38 shows an example of the P2 height distance evaluation.

Figure 38. User trial. P2. Height evaluation example. 12,5 mm

I3. Which is the best angle between the hand attachment and the bow attachment? Which is the most suitable distance?

To make an approximation of which angle would work the best between the grip to the bow attachment two prototypes were used P2 and P5. Figure 40 shows the angle evaluation by using P2. In this case, the angle on top of the bow is analysed as the arrow indicates. Moreover, Figure 39 shows the angle evaluation by using P5. The output angle from E4 (Red cube) to HA1 (Green grip) can be measured, by rotating one component with respect to another as in Figure 39. In addition, the Lego component was attached to the clamp at different lengths to evaluate the best distance from the grip to the bow attachment. These two prototypes, P2 and P5, were assessed with different degrees by tightening their screws.

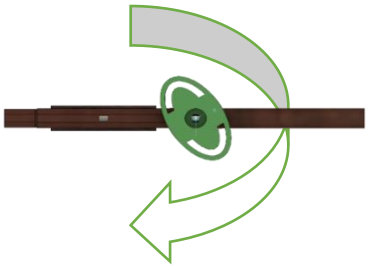


Figure 40. User trial. Angle and length evaluation using P2.

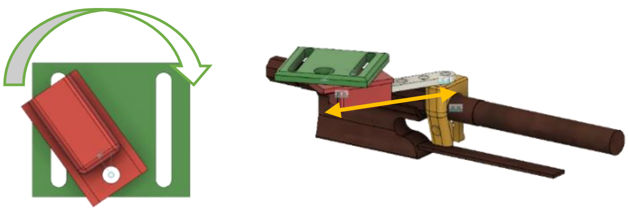


Figure 39. User trial. Angle and length evaluation using P5.

I4. What is the best location to attach the bow holder?

To determine where the future design should be placed P2, P3 and P4 were used. These three prototypes were attached at different parts on the bow by using a clamp mechanism. These clamps were easy to attach at different points along the bow as the arrow indicates in Figure 41.

Figure 41. User trial. P2. Bow holder location along the bow.

I5. How many support points work better for the user? Which is the best distance between them?

P2, P3 AND P4 were employed to evaluate which is the best number of clamps (support points) and to test the distance between them. Figure 42 shows P2, P3 and P4 and their respective number of clamps.

Figure 42. User trial. P2, P3 and P4. Evaluation of the number of necessary support points and distance between them.

I6. Is it better a motion or a motionless bow holder? Which kind of motion mechanism would work better?

To evaluate the motion and diverse mechanisms P2, P3, P4, P5, P6, P7 were used. In all of them the tightness was adjusted while compressing their corresponding screws.

I7. To obtain an imprint of the hand while holding the bow.

P1 was used to create the hand grip mould. The modelling clay acted as a specific grip to the user's hand. 56 grams of modelling clay oven hardening was moulded in a cylindrical shape and set on the top of BA1+E1 combination. After, the user was asked to gently imprint her hand on the plasticine by squeezing it in a gripping position. While the desired shape was accomplished, the modelling clay was removed, and it was introduced to the oven at 110º during 20 min in the oven. Finally, a rigid mould of the natural user gripping position onto the clay was obtained.

I8. To create new concepts with the clay to obtain new ideas.

The user and participants had improvised with the modelling clay and P1 while freely sculpting their ideas.

Figure 43. User trial. To obtain an imprint of the hand and create new concepts with the modelling clay process. Manchester. 28/05/2019

I9. To evaluate the best assembly mechanism. Which is the easiest to use.

Observations of all the assemblies and attachment mechanisms were made during the prototype experience.

I10. To evaluate the most comfortable surface.

HA1 Round grip, HA2 Rectangular grip or the HA3 Plasticine were evaluated by observations and questions to the user to know which touch, shape and surface was the most comfortable for her.

I11. Which are the most valuable prototypes?

At the end of the session, it was asked to the user and her family which the most liked idea was and why.

3 Results

In this section the results gathered through all the activities and methods are explained. The family questionnaire can be checked in the Appendix C. Based on a context mapping approach, observations and a product usability evaluation, the following results were obtained during the trial.

Figure 44. User trial results. HA2 most comfortable location.
Manchester. 28/05/2019

I1. Where is the best location for the hand attachment?

In the middle of the palm close to the digits but without touching them. To set the device around the digits could be a good idea.

I2. Which is the ideal height or distance from the user's body to the bow?

The hand should be as close to the bow as possible. It is easier to the user to use her current capabilities by feeling closer the bow stick.

I3. Which is the best angle between the hand attachment and the bow attachment? Which is the most suitable distance?

Figure 45 left picture shows the most comfortable position of the round grip (HA1), which is a 180º from the bow stick. Figure 45 right picture shows the best angle and length in P5 which are -90 degrees from HA2 and E4, and the maximum length in Lego.

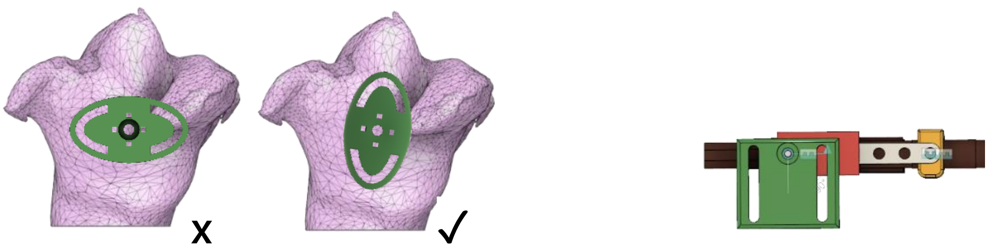


Figure 45 . User trial results. Left picture. Best angle between the hand and the bow attachment in P2. Right picture. Best angle between the hand and the bow attachment in P5.

I4. Where is the best location to attach the bow holder?
On top of the frog, in the middle of it, or touching the frog from its right side. It would depend on the length of the final bow holder. What it is important to consider is that the movement and forces from the arm should be translated into a bow movement through the bow frog area.

I5. How many support points work better for the user? Which is the best distance between them?
She preferred the two point with approximate separation of 55 mm, rather than three points of support or one.

I6. Is it better a motion or a motionless bow holder? Which kind of motion mechanism would work better?
Better tight, no movement. During the trial the user felt more comfortable to use static prototypes and it was easy to her to adapt to them and know how to use them. Between all the motion mechanisms the one that seemed to work the best was the rotational one.

I7. An imprint of the hand while holding the bow.
A successful imprint mould was obtained where it was easily observable where the user applies a bigger gripping force on the surface of the already hardened plasticine.

I8. To create new concepts with the clay to obtain new ideas.
By using plasticine as a generative tool two important ideas emerged. One, her wrist must be parallel to the bow stick, therefore the bow holder should force this position. The user tends to pronate her left hand in excess towards the left by using too much her biggest digit, so the bow holder should oppose this excessive movement. Secondly, other mechanisms should increase the thumb activity while using bowing. Figure 46 shows the results from this activity.

I9. The best assembly mechanism. Which is the easiest to use.
Description of the assemblies and bow attachments used:
BA2
Advantages: It was the easiest to use and with a good fit to the user's bow. It has withstood the necessary stresses during and after the trial.
Disadvantages: it is a very specific design. Each bow would need a different BA2 component specifically designed.
Clamp
Advantages: the idea of having movable small supportive points was very good because it allowed to adapt the bow holder instantly. The user and the other participants could experiment with bow lengths by moving the clamps along the bow. The bow holder could be adapted for the user own growth.

Disadvantages: The material and/or shape were not well selected or designed. Part of clamps could not withstand the stress which they were subjected. They were broken on their lateral, where their walls are thinner.

Comments: The lateral wall width of the clamps was insufficient. PLA was very fragile. It is recommended to print them in PLA flex. Moreover, the screw assembly made the clamps assembly process slower and difficult.

Screw/Nut mechanism

Advantages: Good assembly to tighten and adjust the tightness. Good mechanism to create a rotational motion mechanism.

Disadvantages: The closing mechanism by screws was not easy to use as it needs a large amount of time to assemble and remove the piece. Moreover, it does not give a good appearance or aesthetics to the bow holder.

Fit clip (two different materials).

Different responses were given by fit clips using different kinds of materials.

- Between components made of two different materials. TPE/PLA.

Advantages: It has worked very well.

Disadvantages: This mechanism cannot work by itself if the applied force goes in the same direction as the fit clip mechanism.

- Between two components made of the same material. PLA/PLA.

Two pieces were sliding against each other without finally being attached to each other.

I10. The most comfortable surface.
HA1 with the plane surface touching her skin as shown in the second picture in Figure 46.

I11. Most valuable prototypes

The most valued prototype by the user was P3. The prototype which prompted the most discussion and from which important new ideas were obtained was P1.

Figure 46. User trial results. Best prototypes. P3 and P1 respectively. Manchester. 28/05/2019

4 Conclusions

From the previous results, the ideas have been translated into specific requirements and wishes. By trying diverse ideas, a set of necessary requirements and characteristics were obtained.

Ideas → Specific requirements and wishes

From idea 1 to the wish 1. (I1→W1)

The best location for the grip is in the user's hand palm. It is desirable to not interrupt her fingers and wrist movement with any component.

From idea 2 to the requirement 1. (I2→R1)

The closest to the bow stick the better.

From idea 3 to the wish 3. (I3→W3)

To use a concept similar to HA1 for the hand attachment

From idea 3 to the requirement 2. (I3→R2)

If a similar concept to HA1 is used in future designs, the longer part must be located in the user's hand 180º from the bow stick.

From idea 3 to the requirement 3. (I3→R3)

The bow holder should be placed on the top of the bow stick.

From idea 4 to the requirement 4. (I4→R4)

The bow holder must be attached to the bottom of the bow, on top of the frog at one of its sides, but close to it.

From idea 5 to the wish 4. (I5→W4)

Two separate points of support on the bow.

From idea 5 and 7 to the wish 5. (I5,7→W5)

The bow holder should have a length around 60 mm.

From idea 6 to the requirement 5. (I6→R5)

It must be a motionless device. *(At this stage of the design process, the decision has been made to continue with static designs of the bow holder. Once a good motionless device is created, extra mechanisms will be possible though.)*

From idea 8 to the requirement 6. (I8→R6)

Wrist must be perpendicular to the bow stick.

From idea 8 to the wish 6. (I8→W6)

Thumb activity should be increased and involved in the bowing activity.

From idea 9 to the wish 7. (I9→W7)

Bow attachments preferably made of a slightly flexible material. No fragile material for the bow attachment.

From idea 9 to the wish 8. (I9→W8)

It should be a modular design.

From idea 10 to the requirement 7. (I10→R7)

The surface touching the user's skin must be made of a flexible soft material.

From idea 10 to the wish 9. (I10→W9)

The surface of the grip in contact with the user's skin should be flat.

From idea 11 to the wish 10. (I11→W10)

I11→ W9) P3 and P1 should be taken as a reference for future designs.

Chapter 5.

Hand 3D model acquisition for a custom device design.

An easy and low-cost 3D hand model acquisition method was developed to solve one of the demarcation problems: to obtain accurate measurements and obtain information about the hand's dimensions considering that the user's location restricts the total number of meetings and evaluations of her hand.

1 Introduction. Rapid scanning and measurement for custom device design.

This chapter document a low-cost and easy way of obtaining a 3D model of a hand by casting first the body portion with Dental alginate and Plaster of Paris followed by a hand scan with the Sense 3D scanner.

One of the problems encountered from the beginning of this project was the number of meetings I could have with the user. We are based in two different cities, five hours driving from each other, therefore, it was not easy to meet as many times as needed. Moreover, the idea of having a 3D model was always attractive due to its design possibilities.

1.1 Definition

3D modelling is the representation of a body through points in the 3D space. Combining these points into polygonal shapes, a mesh is created, which is the fundamental unit of a 3D model. These polygonal shapes together represent the surface of an object. On the other hand, a 3D scan is the process of collecting these points from an object and combine them into meshes to construct a 3D model from it [37].

1.2 Interests in rapid scanning for custom device design.

Having a 3D mould of the hand it is interesting due to many reasons. The designing process is faster and more accurate than, for instance, measuring people and recording this information manually. In addition, 3D models allow to design directly on individual's size and proportions. Moreover, a 3D model has information not only about the shape, but also about surface area and volume of the entire selected body parts. Finally, 3D models are easy to send and share, reducing time, money and transport risks [38].

1.3 How the Sense 3D works

Sense 3D scanner Tech specifications can be found in the Appendix F. Sense 3D scanner is a portable short-range HD camera that detects 3D data in real time. The scanner consists of two cameras, one HD colour camera and one high sensitivity infrared projector. To scan an object the camera should be moved around the object to scan. The scanner projects a patterned infrared beam which is detected by the camera located in the middle. In addition, on the top of the scanner there is another camera, a webcom camera, used to obtain information about the real surface colours of the object. Sense 3D scanners includes in the package a *3D systems Sense* ^{tm} software which processes the scanned data and converts it into the 3D model. This software offers a few useful tools to edit, cut and solidify the model [39].

Figure 47. Hand 3D model acquisition. Sense 3D scanner hardware [39]

1.4 Problems encountered in Sense 3D Scanner

The scanner is connected to the computer through a 2-meter USB cable which makes difficult to scan from a long distance from the computer and to scan around a person's hand. In addition, I have found that it is difficult for the device to track objects which are not completely still, as it could be a body part.

2 Methods

The Sense 3D scanner was available for my project and it was easy to use, nevertheless a few problems were encountered when scanning hands. Due to the difficult hand's geometry and the uncontrollable slight movement of the hand in a certain position it was not possible to obtain a direct scan of the hands by using the 3D Sense scanner.

There are other software and hardware to better obtain a direct 3D scan of a hand, but due to money and accessibility they could not be used. After research and meetings with different experts, I have followed the advice of Sarah Day, a prosthesis teacher from Strathclyde University, to make an alginate mould of the hand by using Dental Alginate and Plaster of Paris. In Appendix D more information about the casting process and hand mould generation can be found.

Here below, a description of the steps to get the 3D model of a hand are explained:

1. **To obtain a hand cast**

By using Dental alginate and Plaster of Paris, a mould of a hand is obtained. Figure 48 shows the four main steps for it:

a) To introduce the desired body part into the dental Alginate mixture.
b) To remove the body part from the Alginate and to pour inside the Plaster of Paris mixture.
c) To wait until the Plaster of Paris is dry and to remove afterwards the alginate.
d) Hand mould made of Plaster of Paris is obtained.

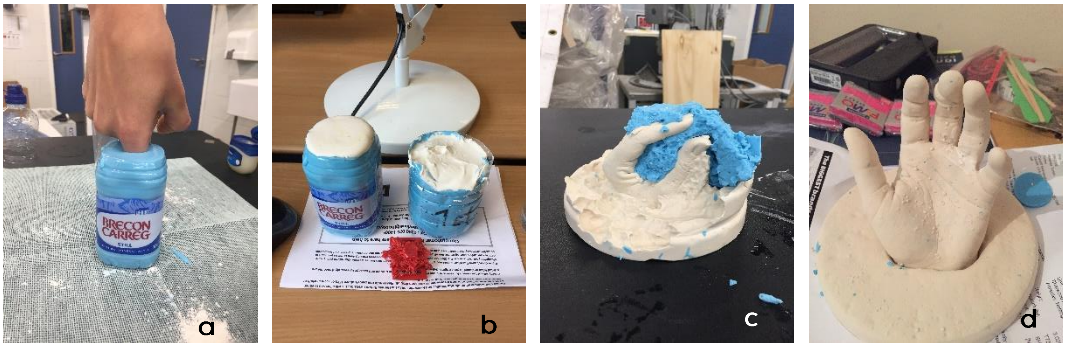


Figure 48. Hand 3D model acquisition. Dental alginate and Plaster of Paris hand casting process.

2. **To scan the hand Plaster of Paris mould with Sense 3D scanner and to edit the scanned object with the 3D systems Sense tm software**

Sense 3D scanner comes with a *3D systems Sense* ^{tm} software which helps you in the scanning/tracking process and which allows you to simply edit the 3D model of the object with a few tools such as *crop, trim, erase, repair and colour.*

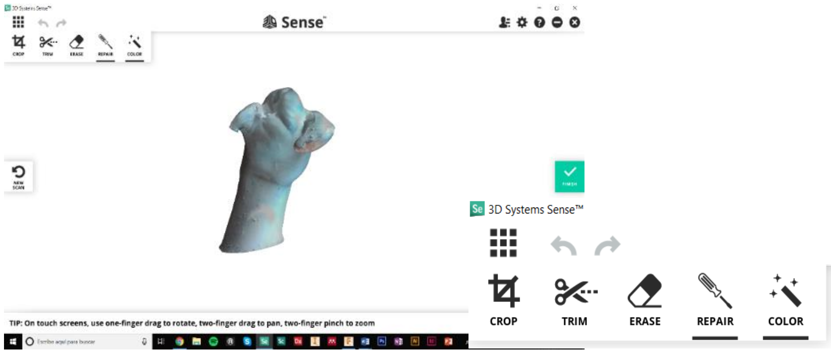


Figure 49. Hand 3D model acquisition. To scan and edit by using 3D systems Sense Software.

Once having the desired model, by clicking "Finish" different saving options are given. The files can be exported to edit in CAD (4.1) or to 3D print (4.2).

3.1 By clicking "Export" and saving files in .obj file format

OBJ files can be inserted in Fusion 360. Commands to follow:

Insert→Insert mesh→ To select .obj file

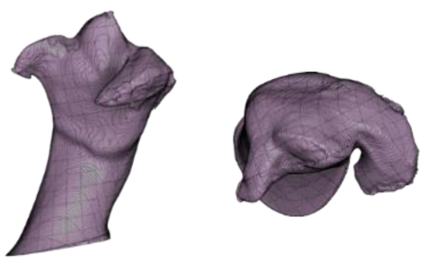


Figure 50. Hand 3D model acquisition. Hand obj file in Fusion 360.

3.2 By clicking "Export" and saving files in .stl file format

Using maker box software, the stl can be opened and prepared for 3D printing.

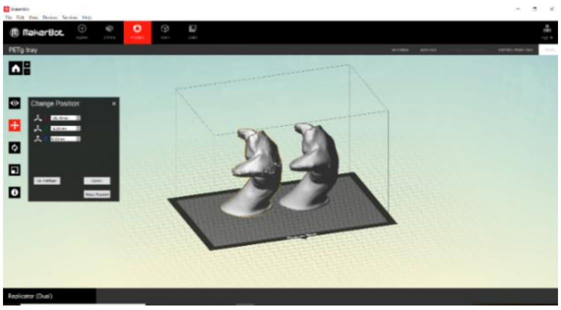


Figure 51. Hand 3D model acquisition. STL. files to 3D print. Maker box software.

4.1 To edit and use it to develop custom specific devices.

To create form→Utilities→Convert→"Quad mesh to t-splines"

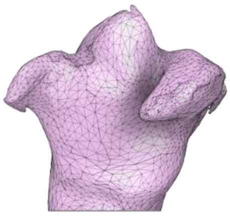


Figure 52. Hand 3D model acquisition. User's hand in t-spline form (Fusion 360).

4.2 To print.

To insert the file into the 3D printer and wait the necessary time.

Figure 53. Hand 3D model acquisition. User' hand printed in PLA

3 Results and discussion

- Sense 3D scanner was found to follow the track without any problem when the object to track was still in a static position. It is recommended to leave a circular or symmetrical shape at the bottom of the mould, which makes easier for the scanner to follow the track.

- After having the model, it is easy to share and print the hand files which means that less time and money are involved in working with 3D models.

- Furthermore, having a 3D model of a hand has enabled the possibility of designing customized bow holder devices and evaluating specific measurements and proportions without time or distance constrictions.

- The accuracy level between the real hand and the 3D model has not been already tested. But proportions and tape measurements taken by hand correspond reasonably with the model measurements.

Chapter 6.
Synthesis II

In this chapter, the new specific requirements will be considered to develop a new design. The carefully chosen concept is further detailed and developed. The chapter consists on the following sections:

- *Introduction*
- *Idea generation*
- *Developing the last concept*
- *Manufacturing the final prototypes*
- *Results of the final prototypes*

1 Introduction

From the results and conclusions obtained in the user trial new ideas were created to design a customized bow holder. A motionless device was developed to assure user's control over the device. Furthermore, some aspects such as the wrist angle in relation to the bow and to increase the thumb interaction with bow holder were deeply considered.

2 Idea generation

This project describes a specific, iterative and participatory design process. Therefore, some of the same steps developed in Synthesis I are repeated. For instance, the idea generation. Nevertheless, in this case, due to the already accumulated experience a general approach of the bow holder design was done instead of subdividing the design in its functional parts. The new ideas were mainly born from the most valued prototypes, P1 and P3. They are shown in Figure 54. Three different ideas were generated and sketched.

Figure 54. Synthesis II. Photo summary of the best ideas in the UT. P1 and P3. Manchester. 28/05/2019

2.1 "Sole imprint". One piece

The idea of this concept was to imitate the therapeutically feet soles to redistribute the position of the hand to accomplish the desired functions and angles. This idea was conceived from the evaluation of the FIMO model obtained in the user trial. Different thickness in the material were observed in the remaining model, specifically adapted to the user's hand. Furthermore, by adding more material at different areas, it was thought that it could be possible to change the hand position related to it. To further generate this concept, different sketches using level curves were done. Figure 55 shows level curves while evaluating the different thicknesses in the surface. Different line densities and different colours meant different thickness of the material. The projection of all these plane curves in a common plane give rise to the level representation. After having a clear idea of which areas needed a thinner and thicken section a 3D model was developed.

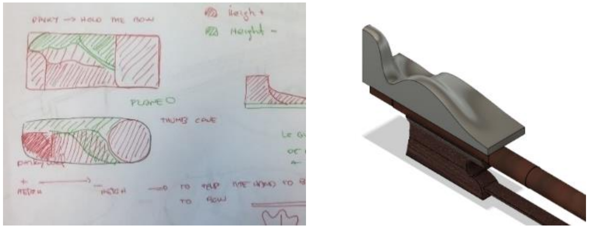


Figure 55. Synthesis II. Sole imprint imitation

2.2 Two modules. Thumb improvement. Pinkie elevation.

This concept is a two-module system made of a pinkie elevation module, helping the user to use her biggest finger in the appropriate way. In addition, a thumb slot module is included to increase the thumb mobility and help the user to hold the bow. This concept would have had to be done in a perfect fit for the user's hand. Figure 56 shows the sketch and 3D model of this concept. It is shown in two colours the different modules.

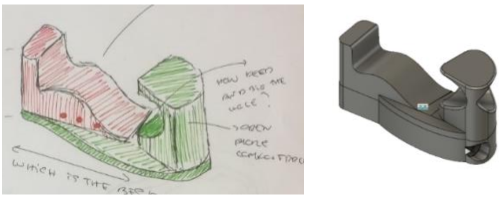


Figure 56. Synthesis II. Two module-concept

2.3 Four modules. Palm support. Thumb improvement. Hook for pinkie elevation.

Finally, based on the round grip, the pre-concept HA1, a modular system was created. This approach is a modular system made of four sub-systems; the palm support, a bow attachment, a thumb slot module and a hook module to support correct the wrist angle. It is called "hook" due to its resemblance to the appearance of a hook. The palm support is the central element, and the remaining parts are linked to it through different mechanisms.

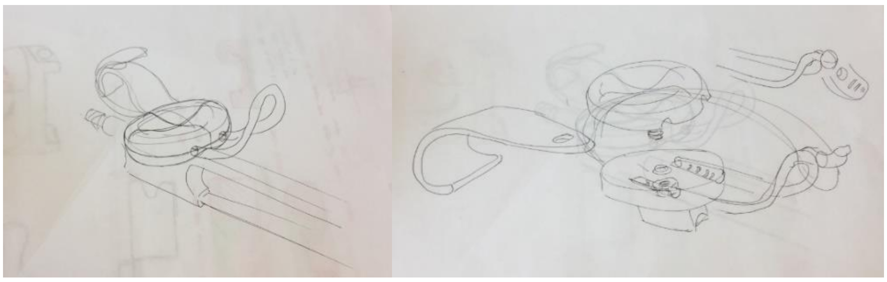


Figure 57. Synthesis II. Four module-concept

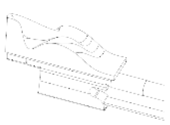
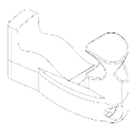
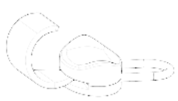
2.4 Concept selection. Working towards the final concept

To select the final concept a weighted objective method was applied. This method consists on comparing the three design concepts based on the overall value of each design concept. In this case, there are three design alternatives and it is necessary to take a decision about which concept should be further developed. The highest-scoring proposal does not have to be necessarily the winner, but it will help to analyse and compare each of alternatives. To evaluate the concepts the applicable requirements and wishes described in the of User trial chapter were used. Each criterion has a different value or weight depending on their importance [23]. Requirements will be evaluated with a punctuation of 15 and the wishes with a punctuation of 10. Each requirements and wish are evaluated from 0 to 10. The final score is multiplied for the given value for each feature.

	Features	Weight
Requirements	1. The device must be motionless	15
	2. The device must have a reduced width	15
	3. The device must correct the angle wrist/bow	15
	4. The device must be able to be attached nearby the frog	15
Wishes	5. P3 and P1 are considered	10
	6. The device does not interrupt the current capabilities of the user	10
	7. Modular design	10
	8. Thumb is included in the bowing action	10
	Total score	**100**

Table 7. Synthesis II. Applicable requirements and wishes for the weighted objective method

Table 8 shows the most valued design, which was the four modules bow-holder. This model will be further described and develop.

Score 1	**Total**	**Score 2**	**Total**	**Score 3**	**Total**
10	150	8	120	6	90
8	120	8	120	10	150
8	120	10	150	10	150
10	150	10	150	10	150
0	0	5	50	10	100
10	100	8	80	10	100
0	0	6	60	10	100

0	0	10	100	10	100
Total score	**640**	**Total score**	**830**	**Total score**	**940**

Table 8. Synthesis II. Final scores in the weight objective method

3 Developing the last concept

3.1 CAD-simulation

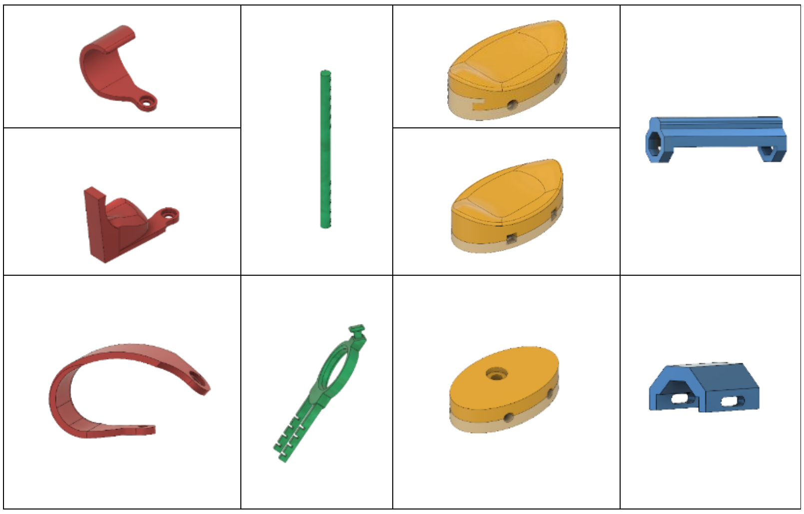
At this stage, the 3D model of the user's hand was already obtained, and it was possible to use it to evaluate the components with the specific measurements and proportions. In addition, it was possible to start to design directly on the 3D model by using the mesh and free form modelling options in Fusion 360. These two options offer the ability to edit and repair imported scans or mesh models respectively, including STL and OBJ files, and to create complex sub-divisional surfaces with T-splines and edit them with intuitive push-pull gestures [40] In this way, more accurate and specific devices were developed and are expected to be developed in future stages of the project. Figure 58 shows one of the last designs from this project.

Figure 58. Synthesis II. Specific design adapted to the user's hand.

3.2 Modular components

The final design is a modular system comprising four sub-systems; the palm support, a bow attachment, a thumb slot module and a support and angle correction module or hook module called like that due to its resemblance to the appearance of a hook. The palm support is the central element, and the remaining parts are linked to it through different mechanisms. With the aim of arriving to a successful final design, different variations from each module were developed to test them and further determine the product specification and requirements. Each module has a specific task and for each module there are a few variations with diverse characteristics.

Table 9. Synthesis II. Towards the final concept.



Technical draws of the final design can be found in Appendix F.

3.2.1 Palm support

This module was conceived from the pre-concept HA1 and it is the central and main component of the bow holder. It has an oval shape and it is made up of 2 parts - a top part in contact with the user's palm and a bottom part assembled with the bow attachment module. These two sub-modules are thought in this way to create an easy assembly mechanism with the hook and the thumb grip modules. The hook goes through a cylindrical socket in the bottom palm support component, so the post on the palm support can stick through and be attached to the Hook. Figure 60 shows this joint mechanism with a range of motion restriction of 80º. The user can adapt the angle between these two modules at any moment. Moreover, the thumb grip is attached to the palm support from its right side by using a press fit mechanism reinforced by 4 notches. This press fit mechanism is shown in Figure 59. The user can adapt the thumb grip length by assembling it to the palm support at 4 different notches.

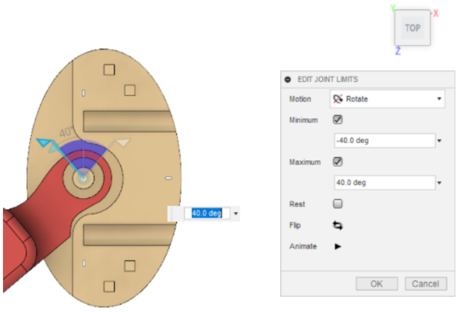


Figure 60. Hook-Palm support assembly. Range of movement of 80º.

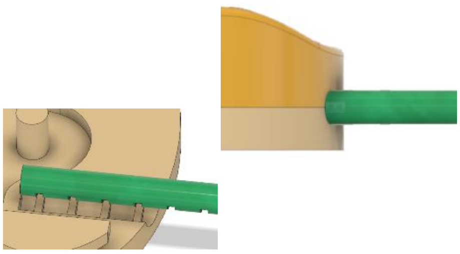


Figure 59. Assembly mechanisms between the thumb grip and the palm support.

There are three variations of the palm support module which differ from each other in the 2 sub-system assembly mechanism, the thumb grip opening shape and the geometry of the top part component.

G1. Fit clip by rotation
In this case the components are assembled by turning one with respect to the other until they are in the correct position. The assembly holes for the thumb grip module assembly are circular in shape and the shape of the top sub module has a negative slope towards the centre.

Closing mechanism
1.- Connect mechanism by a post in the centre of the bottom palm support component with the hole in the top part of the palm support.

2.-Turn 90º degrees from each other, fitting the top with the bottom part until they are in the correct position.

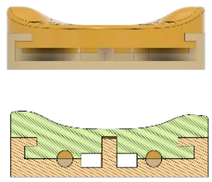


Figure 61. G1- Fit clip by rotation

G2. Press fit
In this case the components are assembled by pressing one against the other until their surfaces are in contact. In the top image in Figure 62 the distribution of the posts is shown. There is a central post in the middle and four other small prismatic posts, two at each end of the ellipse. The assembly holes for the thumb grip module joint are square and the shape of the top sub module has a negative slope towards the centre.

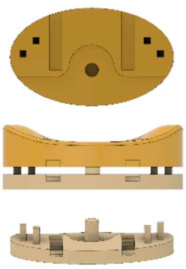


Figure 62. G2 Press fit

Closing mechanism
1.- Press fit both sub-modules by squeezing them against each other.

G3. Screw joint
In the last case the components are assembled one with respect to the other until they are in the correct position and completely tight. The assembly holes for the thumb grip module assembly are circular in shape and the top sub module has a plane surface, which will be covered with a biocompatible soft material.

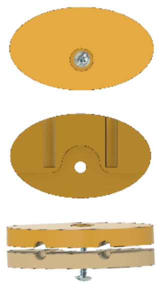


Figure 63.G3. Screw joint

Closing mechanism
1.- Fit a nut at the top, covering the hole seen in the top image in Figure 63. From the bottom part insert the M4 screw and fit it into the nut until the 2 sub-modules are tightly connected.

3.2.2 Hook. Hand angle correction.

Hook shape piece to support and hold the user’s pinkie. At the same time, this piece restricts the pinkie movement and corrects the wrist angle in relation to the bow. In Figure 64 four different parameters used in the development of the following 3 variations are explained. Firstly, the height (h) from the bottom of the hook which is attached to the base of the palm support to evaluate at which height the angle correction of the wrist will be the best. Secondly, the length (l) describing which is the necessary

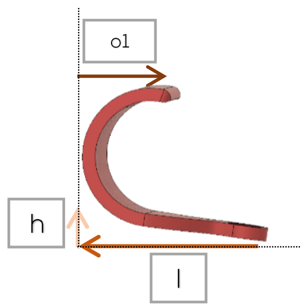


Figure 64. Hook. Hand angle correction.

length from the palm support to the end of the hook to hold and grip the pinkie and the left side of the palm. And finally, there are two parameters defining the opening (O1 and O2). O1 defines how far the material goes within the hand and O2 the width of the hook, where the pinkie will be placed. More information about the measurements can be found in technical drawings in the Appendix G.

H1. Hook concept 1

It secures and restricts pinkie position and mobility and adds a little bit of elevation to the pinkie in relation with the palm. In Table 10, the different measurements are explained.

Table 10. H1 parameters definition

<table>
<tr><td rowspan="4">
Figure 65. H1</td><td>Elevation from the Palm support module base</td><td>6,77 mm</td></tr>
<tr><td>Distance over the wrist</td><td>O2= 26,97 mm opening O1= 20,02 mm</td></tr>
<tr><td>Width of the piece</td><td>24 mm</td></tr>
<tr><td>Length from the centre of the assembly</td><td>35,28 mm</td></tr>
</table>

H2. Hook concept 2

Table 11. H1 parameters definition

This variation offers a freedom of movement in the user's pinkie and an its elevation and consequently a change in the angle of the wrist in relation with the bow.

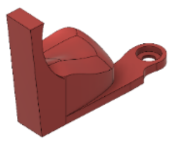
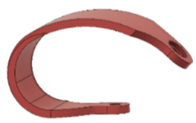
<table>
<tr><td rowspan="4">
Figure 66. H2</td><td>Elevation from the Palm support module base</td><td>20,4 mm</td></tr>
<tr><td>Distance over the wrist</td><td>0 mm</td></tr>
<tr><td>Width of the piece</td><td>20,75 mm</td></tr>
<tr><td>Length from the centre of the assembly</td><td>55,9 mm</td></tr>
</table>

Table 12. H2 parameters definition

H3. Hook concept 3

Securing the left side of the hand using a bracelet. There is almost no change of the wrist angle.

<table>
<tr><td rowspan="4">
Figure 67. H3</td><td>Elevation from the Palm support module base</td><td>4,46 mm</td></tr>
<tr><td>Distance over the wrist</td><td>68,82 mm 27,33 mm opening</td></tr>
<tr><td>Width of the piece</td><td>26 mm</td></tr>
<tr><td>Length from the centre of the assembly</td><td>36, 88 mm</td></tr>
</table>

3.2.3 Thumb slot

The objective of this module is to encircle the user's thumb and involve the current thumb sensitivity and movement in the act of bowing. Moreover, by gripping the thumb we add another point of support into the bow holder. The thumb grip is attached to the palm support from its right side by using a press fit mechanism reinforced by 4 notches as it is shown in the Figure 68. The user can adapt the length from the thumb grip by assembling it from notch number 1 to number 4.

There are 2 variations with different characteristics:

T1. Single band
The rope surrounds the user's thumb and involves the thumb in the bow holder structure. It would encircle the user's thumb and it is attached to the palm support by fitting it between the top and the bottom part that forms the palm support.

Figure 68. Single band. Thumb slot T1

T2. Ring
It is a specific thumb ring attached to the palm support by two ropes following the same assembly mechanism as T1. T2 has the possibility of being attached to the bracelet described in H3 by a fit clip.

Figure 69. Ring. Thumb slot T2

3.2.4 Bow attachment

BA2. Attachment to the frog
Rigid attachment to the bow which provides a perfect fit to the the frog. It was already used in synthesis II.

Figure 70. Attachment to the frog. Bow attachment. BA2

BA3. Zip tie attachment
As BA1 was not successful, it was desired to continue trying different ways to attach the bow holder to the bow. An easy and strong method is by using zip ties. BA3 provides an attachment with the bow holder palm support and it has two gaps to slide the zip ties through, enabling their use.

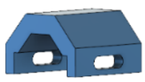


Figure 71. Zip tie attachment. Bow attachment. BA3

3 Manufacturing the final prototypes

Same process has been followed to fabricate the prototypes as in *Prototype production and material selection* in *Synthesis I*.

TPE and PLA were used to fabricate the prototypes due to lack of PLA flex material. Bow attachment elements are thought to be printed in PLA flex in future approaches. Pieces on need of flexibility and in contact with the user's skin were made of TPE. Other parts were printed in PLA. As well, the components orientation was considered in such a way that they would lie on the side to minimize the amount of support material and in a way that the component will stand better stresses and forces. Figure 72 and 73 show the set up in Cura and Market forget of the different components.

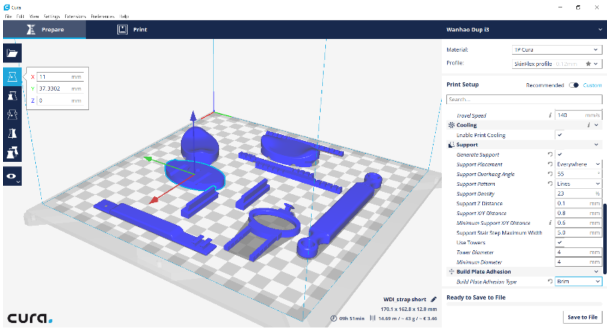


Figure 72. Synthesis II. Cura software. 3D printing software settings and disposition of the TPE components lying in its best side to minimized supportive structures and withstand the necessary forces.

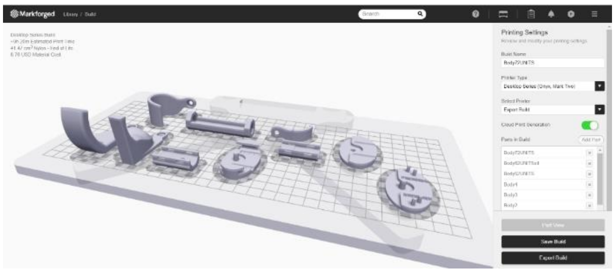


Figure 73. Synthesis II. Market forged software. 3D printing software settings and disposition of the PLA components lying in its best side to minimized supportive structures and withstand the necessary forces.

4 Results of the final prototypes

The four sub-systems; the palm support, the bow attachment, the thumb slot and the hook modules can be fitted by using different combinations. A future second User Trial need to be developed to analyse the final prototypes and determine further product specification and requirements. On the other hand, by having the final low fidelity prototypes and the 3D printed model of the hand, some mechanisms and conclusions could be already assessed.

Figure 74. Synthesis II. 3D printed hand with the final prototype fitted on it

Dimensions

There was not enough time to design over the 3D model all the components and make their measurements accurate enough. Therefore, some of the components need to be re-dimension to obtain a better fit such as H1 and H2. Moreover, to have a better fit with the user's skin the hook module material should be slightly more elastic as it was originally thought. Nevertheless, to have the prototypes in PLA helped us to analyse and gain a better idea about which corrections need be already done. In addition, T1 is very short to surrounds the user's thumb

T2 was already designed over the 3D model and its physical version seems to have a very good dimensions and fit over the 3D printed hand. Figure 74 shows the thumb slot T2 fitted on the 3D hand.

Palm closing mechanisms

The palm support is the central element, and the remaining parts are linked to it. The palm support is made of 2 components. Three different palm support were fabricated, each of them using different assembly mechanisms: the fit clip by rotation, the press fit and screw joint. The most valued assembly mechanism seems to be the fit clip. It is easy to use, comfortable and reliable. The screw joint is realisable, but it takes more time to assembly each of its part, therefore it is not as easy to use as the fit clip mechanism. Finally, the press fit is the easiest to use, but it does not seem to be very reliable while using it.

Figure 75 shows three final prototypes made of different module combinations.

Figure 75. Final prototypes already printed and assembled

Chapter 7. Evaluation

It involves collecting and analysing information about the project, its characteristics, and outcomes. The design criteria are used to evaluate the design and the conclusions are established.

1 Results

A customized, low-cost, body-powered prosthesis design of a cello bow holder for a 7-year old girl with a left-hand disability was created.

- A list of requirements and wishes was created to guide the design process and evaluate a reliable bow holder device for the end-user.

- Rapid prototyping techniques and FDM 3D printing processes were applied to fabricate different prototypes.

- The final concept is a modular design. In this way the device can be instantly adapted to the user current necessities. Moreover, having a modular device will make easier to work in the future towards the ambition of creating an opensource and modifiable design to ensure others with similar difficulties can adapt the device for their specific needs.

2 Discussion

The solution was technical and restricted by several demarcations. The most important limitations were time and money. In order to approach the design process considering the money and time restrictions 3D printing and rapid prototyping methods allowed me to develop low-cost and novel solutions to face the design problem by using simple mechanisms and economical materials. Moreover, another remarkable demarcation's problem was the reduced possible number of meetings with the final user. This problem was solved by developing a method to obtain a 3D model of the user's hand. This model assures a future better customization and modification of the final device to effectively meet the needs of the end user.

Finally, a customized, low-cost, body-powered prosthesis design of a cello bow holder for a 7-year old girl with a left-hand disability was created. Nevertheless, in order to produce a final device completely useful for the user it is necessary to continue with detailing design and to develop more trials with the final user.

2.1 Requirements and wishes evaluation

The final bow holder design is evaluated by each of the requirements and wishes created along the project. (Chapter 2. Design criteria).

2.2 General requirements

2.2.1 Comfortability

All the requirements to obtain a comfortable device were accomplished. The material in contact with the limb has a good shape and is made of a soft material. It was tested in User Trial 1. Secondly, the final bow holder device has a correct weight (< 100g). and it fits with the user's hand.

Future improvements are needed to be made to minimize the width of the bow holder and allow the user to be as close to the bow as possible.

2.2.2 Function/Control

Prototypes on which the final design was based were tested in terms of function and control in the user trial, with encouraging results.

2.2.3 Mechanical Requirements

The prototype is a body powered device. Nevertheless, it is in an early stage of the design to test forces and stresses on it. Furthermore, improvements and test are needed to assure that the bow attachment is well connected to the bow.

2.2.4 Materials and Manufacturing methods

Low cost and easy to manufacture methods were used. Low cost and biocompatible skin materials were used. FDM 3D printing rules were considered while designing components in CAD.

2.2.5 Safety

The current design does not use toxic materials, to not produce rashes or other negative body reactions, to not cause injuries or pain to any part of the user's body.

2.2.6 Practical considerations

The user's favourite prototype was used to develop the final design (P3), which assures that the design will be accepted and liked by the user. Furthermore, in the final manufacturing process the user's favourite colours, green and yellow, will be used. An easy to use device was accomplished. The final prototype was assembled in less than 15 minutes.

2.3 General wishes

The bow holder is attached to the hand in the least used area, without interrupting the user's current capabilities.

2.4 Specific user requirements

The final prototype was designed to accomplish the following specific requirements. A second user trial is needed to assure that these objectives were accomplished.

The final prototype was designed to have the hand as close to the bow as possible, which means to reduce height and distance from the bow holder to the bow as possible. A module was added to correct the hand position with the aim of having the wrist parallel to the bow stick. In addition, the thumb possibilities can increase by using the thumb slot module. The whole design is a motionless device because it helps the user to evaluate and use the bow holder.

2.5 Specific user wishes

A modular design was developed to offer adjustability to the user. The material connection with the user's skin was made of TPE, a flexible biocompatible material already tested and accepted by the user.

3 Conclusions

This project describes the designing process and development of a customized, low-cost, body-powered prosthesis design of a cello bow holder for a 7-year old girl with a left-hand disability. Novel design solutions designed in Fusion 360 and specifically FDM fabricated using different low-cost materials were developed. Furthermore, a 3D model acquisition method for obtaining 3D models from body extremities was described.

The final design is a modular body powered device in 4 parts connected to each other with easy assembly mechanisms. The final prototype was successfully 3D printed and manufactured it. Many of the requirements and wishes created to guide the design process were successfully accomplished such as comfortability, material and manufacturing methods, safety, practical considerations and specific requirements. On the other hand, some of the requirements as the mechanical and the function and control considerations need extra improvements and tests.

Further steps involve continuing developing the designs by using the 3D model of the hand and the freeform CAD tools. Moreover, future work will involve testing the final prototypes and carrying out its necessary optimisations. Possible adaptations of the modular device for people with the same needs and similar disabilities are also expected to be done.

Ethics paragraph

1. Societal impact: why is your research important? What is the added value for society?

People with limb difference aspiring to play musical instruments have a very limited choice of devices that allow them to reach their potential. In Europe, 14% of the people have a disability. [1] If just a few percent of them want to have the possibility of making music, they should have it. People with disabilities are unsupported and undermined, and sometimes they are left without a voice. Some of them want to have a career in music and become a professional instrument player, but they cannot because no tool exists for them just because no musical instruments have been designed with them in mind. Existing solutions are hard to come by, due to people limited access to design and manufacturing expertise necessary to develop highly individualised solutions. Through design and technology, this project searches to increase the social equality and people with limb difference opportunities.

2. Identification of the key ethical issues.

This research has been a human centre design approach, where the main participant has been a 7-year-old child. Researching with children implies to have a special treat and consideration with the participants due to their vulnerable status. [41] The following ethical points were consciously considered along the project: confidentiality, parental informed consent and physical and psychological risks.

A participant information consent has been done directly via parents. Important points were made clear such as: purpose of the study, possible disadvantages, confidentiality, and who were the people responsible of the research. Moreover, they were informed that at every moment they could change their mind and withdraw from the study without giving any reason. In addition, to disseminate a good practice, feedback from any finding from the child and the design process along the research was given to the participant and their parents.

On the other hand, it was important to explain clearly through a consent form the limits of the project and its confidentiality. For instance, it was explained that information and data related with the user would appear in two master theses, one for the Czech technical university of Prague and other for the University of Groningen. Moreover, the work done could be openly available.

All trials and practices were carefully prepared and organized beforehand to avoid any harm or pain from the participant. Things that might go wrong were identified and any possible risk was avoided. For example, the hand casting was trained and prepared in advance to not hesitate about it when developing the activity with the participant. Furthermore, when organizing and preparing trials and activities with the child, the content was prepared in accordance to her age and maturity [42]. Satisfying patients’ expectations presents an important ethical problem as shown in a study of upper limb exoskeleton device for stroke patients [43]. Therefore, huge effort was made to ensure that expectations were managed and met as far as possible.

A scanner of the original signed consent form and the information sheet provided to the family form can be checked in the following pages.

Consent form

Consent Form

PARTICIPANT NAME: F. RISTE
TITLE OF PROJECT: Bow holder for cellist/violinist with limb difference
NAME OF RESEARCHER: Clara Rionda

PARTICIPANT TO COMPLETE

Please initial the boxes to indicate your agreement with the following statements -

Statement	Initial
1. I confirm that I have read the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily	[illegible]
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason	[illegible]
3. I agree to notes to be taken and being videos/photos were taken during the study	[illegible]
4. I agree to the use of anonymised quotes in research publications	[illegible]
5. I agree to take part in the above study	[illegible]

Please sign and date:

Signature: [illegible] Date: 28/5/19

RESEARCHER TAKING CONSENT TO COMPLETE

Signature: [illegible] Date: 28/5/19

PDR
Cardiff Metropolitan University
Cardiff, United Kingdom
CF5 2YB
Tel: +44 (0) 29 2041 6725
Fax: +44 (0) 29 2041 6973
Email: info@pdronline.co.uk
Web: www.pdronline.co.uk

Participant Information Sheet

Study Title: Bow holders for cellists and violinists with limb difference.
Introduction:
You are being invited to take part in a research project funded and carried out by PDR (International Centre for Design Research). The project has been conceived through conversations with a UK-based charity, OHMI, who develop and adapt musical instruments for people with physical disabilities.

This is a final project being undertaken as part a from a European double degree Master's programme in Biomedical Engineering. The corresponding universities related to this project are the University of Groningen and the Czech Technical University in Prague.

Before you decide if you would like to take part, we would like to explain to you why the study is being carried out, what it will involve and your role. Please read the information leaflet carefully and discuss it with your family and friends if necessary. If there are any aspects of the information sheet that are not clear, then please contact the named Chief Investigator listed at the end of the sheet.

What is the purpose of the study?
This project seeks to understand the mechanics, user needs, and technical design considerations required to fabricate a bow holder that can be used by a 7year-old girl with a left-hand disability. The aim is to create a comfortable, functional, reliable and appealing device.

The project will involve concept design, fabrication and evaluation through user trials.

Do I have to take part?

- **You do not have to take part.** However, if you decide to take part you can keep this information sheet, you will be asked to sign a consent form that shows us that you have understood what the study involves and that you are happy to take part.

- You can change your mind and withdraw from the study at any time without giving a reason.

What will happen to me if I take part?
There will be future meetings that require your involvement:

- Approximately 1-2hr meeting to discuss device requirements, 3D scan/measure your child’s hand/forearm.
- User trials to try a range of prototypes. We estimate this will take place in April.
- Approximately 1-2hr meeting to review the refined design concepts. We estimate this will need to take place towards the end of May to early June.

What will I have to do?
Once you have had all your questions answered, we will ask you to sign a consent form to say you are happy to take part in this study (you can still withdraw at any stage without giving a reason).

What are the possible disadvantages of taking part in the study?

The researchers are not aware of any risks or disadvantages to you of taking part in this study.

What if there is a problem?
Should a complaint relate directly to the research, you are requested to inform the Chief Investigator, Clara Rionda.
If you remain unhappy and wish to complain formally, you can do this through the Cardiff Metropolitan University complaints procedure. Details can be obtained upon request.

Will my taking part in the study be confidential?
Any details about you will remain strictly confidential. Your consent forms, discussion notes, and 3D scans of your child will be held securely for the project duration. Photos of the hand/forearm will be shared with colleagues in PDR and OHMI.

Data and case description will appear in two master theses, one for the Czech technical university of Prague and other for the University of Groningen. Work done will be openly available.
What will happen to the results of the study?
Data from the study will be presented in the form of a report to the PDR team, OHMI, the Czech technical university and the University of Groningen.

Who is organising the study?
The study is being organised by PDR, who are a research and development unit within Cardiff Metropolitan University.

Who has reviewed the study?
The study has been reviewed by: Cardiff Metropolitan University Ethics Committee.

Contact Information details

- The study team contact details are available below. Please contact the team if you have any questions regarding the study. If following the study, you have any symptoms that you think may be related to the study please do not hesitate to contact the team.

- Thank you for considering taking part in this research study. You will receive a copy of this information sheet and a signed consent form to keep should you wish take part.

Contacts for further information:

The Chief Investigator, Clara Rionda can be contacted at:
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Appendix A
FDM materials

Rigid materials

1. **PLA.**

PLA (Poly-Lactic Acid), a common 3D-printing material, biocompatible and non-toxic [44]. It offers limited mechanical properties and does not work well at temperature extremes. For instance, it will be deformed relatively easily above around 50 degC. This feature can be useful – a hairdryer can be used to heat and manipulate a shape to make minor adjustments.

- Excellent visual quality (+)
- Easy to print with (+)
- Low impact strength (-)

Table 13. Appendix A. FDM materials. Mechanical Properties of PLA from [45].

Property	Value	Unit
Tensile modulus	2346.5	MPa
Tensile stress at yield	49.5	MPa
Tensile stress at break	45.6	MPa
Elongation at yield	3.3	%
Elongation at break	5.2	%
Flexural strength	103.0	MPa
Flexural modulus	3150.0	MPa

2. **Nylon**

The nylon is tough and slightly flexible. It can also be stiffened with local carbon fibre infills. The material is more expensive than the other materials used in this project, but still it has an affordable prize [46]. Studies have shown the use of Nylon in Orthosis assuring its skin compatibility [47].

- High strength (+)
- Excellent wear and chemical resistance (+)
- Low humidity resistance (-)

Table 14. Appendix A. FDM materials. Mechanical Properties of Nylon from [46]

Property	Value	Unit
Tensile modulus	1282 MPa (XZ Axis) 1138 MPa (ZX Axis)	MPa
Tensile stress	32 MPa (XZ Axis) 28 MPa (ZX Axis)	MPa
Elongation at yield	2.4% (XZ Axis) 2.7% (ZX Axis)	
Elongation at break	30% (XZ Axis) 5.4% (ZX Axis)	
Flexural strength	67 MPa (XZ Axis) 61 MPa(ZX Axis)	MPa
Flexural modulus	1,276 MPa (XZ Axis) 1,180 MPa(ZX Axis)	MPa

Semiflexible materials

1. **TPE**

Thermoplastic Elastomers (TPE) are flexible materials that can be stretched to twice their length when they are at room temperature. They can be used in contact with the skin without creating any kind of reaction. They are used in the fabrication of elastomeric functional parts for applications such as sports equipment, shoe midsoles, or patient-specific orthopaedic insoles [48].

- Very flexible (+)
- Difficult to print accurately (-)

Table 15. Appendix A. FDM materials. Mechanical Properties of TPE [49]

Property	Value	Unit
Hardness	52	shore A
Elongation at Break	>600	%
Tensile Strength	10	MPa

4 PLA flex

Soft-Flexible PLA filament is a flexible filament with properties durable rubber. It is useful for parts that need to be flexible. They are durable materials that do not break when bending.

Table 16. Appendix A. FDM materials. Mechanical properties of the PLA flex [50]

Property	Value	Unit
Tensile modulus	390 MPa	MPa
Tensile strength	17 MPa	MPa
Elongation at break	300	%

Appendix B

Parents' questionnaire

- Medical description of Erin's condition. Medical information.

"My daughter was born with a lymphatic venous malformation which has change and evolved as she has grown- although the hand has remained unchanged."

- Questionnaire

    - *General questions:*

1. Does she use for any other kind of activity an adaptive device for her left hand?

"She has an adapted brace and bike handles for her bike."

    - *Sensitivity/Pain evaluation/Constrictions*

2. Does she have a specific pain or uncomfortable position in her left hand?

"Only really if she's knocked it or bruised it- her left arm and hand do bruise easily."

3. The pressure of a hand-band around her palm would be painful or very uncomfortable? Does she have any kind of sensitivity to cold/warm temperatures?

"No sensitivity to temperature. As long as a hand band is not very tight, it should be ok for her."

4. Limitations in terms of which materials she can touch.

"None."

    - *Functional use:*

5. Does she go to a physiotherapist or occupational therapist?

"She has physiotherapy and sees an occupational therapist occasionally at BCH-we can access the services when we need them."

6. Which kind of activities does she do her left hand? Does she have to do training exercises?

"She has to do training exercises to strengthen the muscles in her whole left arm and we encourage her to do bilateral activities to made sure that arm stays as strong as possible."

Appendix C

Dental alginate and Plaster of Paris experience

1. Material selection

Alginate: Due to its biocompatibility, simple impression and cost-effectiveness Alginate was chosen to create the user's hand and forearm mould. The Alginate is an elastic, irreversible hydrocolloid impression material famously used in the dental practice. [51] It will be used to make a negative impression of a subject's extremity to make posterior rigid cast also called a replica or reproduction of the original section of the upper limb under study. [52]

Plaster: There are plenty of casting compounds to make rigid and inexpensive moulds and casts as resin, fiberglass, cement, gypsums and other materials. Due to its cost-effectiveness and simple use Hydrostone Plaster and Plaster of Paris were the pre-selected materials. Finally, due to its availability and price Plaster of Paris was selected. Hydrostone plaster is hardener than Plaster of Paris, which means that the final mould would be more resistant. Nevertheless, Plaster of Paris is resistant enough for our purpose.

Petroleum Jelly (Vaseline): Petroleum jelly is a mixture of natural waxes and mineral oils that together lock moisture in skin, moisturizing it to repair and relieve dryness. It will be used to make easier relieving the body part from the alginate mould. [53]

2. Casting materials and preparation procedure

Important to have all the materials and tools ready to go before to start applying the procedure. First, to prepare the Plaster of Paris mixture and after to start with the alginate procedure. In this way, the Plaster of Paris mixtures will be ready when the alginate preparation will be done.

SUPPLIES NEEDED

Mould bucket
Materials staging containers,
scooping cups
Vaseline
Alginate mixture
Plaster of Paris mixture

ALGINATE MIXTURE.

Dental Alginate (approx. 3-parts of powder for 1-part of water)
Water
Bowl/Bucket
Wide-blade spatula
Measuring cup
Commonly used alginate materials are supplied in containers.

PLASTER OF PARIS MIXTURE. [54] [55]

Plaster of Paris Powder (approx. 2-parts of powder for 1-part of water)
Water
Mixing container
Spoon or spatula
Measuring cup
Mould
Newspapers or plastic mat

SAFETY TIPS: caution should be taken to avoid getting the powder into the eyes and nose. Both materials are not toxic or have any risk for kids and adults.

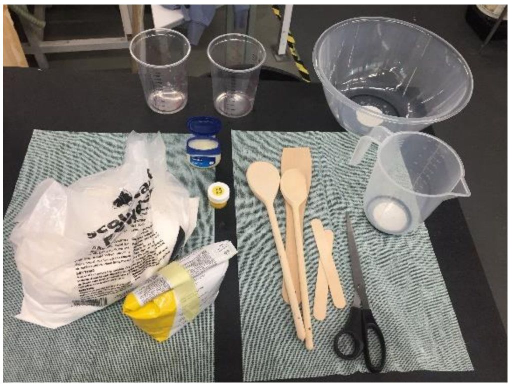


Figure 76. Casting materials

Plaster of Paris procedure [54] [55]

1. To measure the powder and water proportion in two different containers.
2. To add the powder into the water by sprinkling the powder over the water carefully without creating air bubbles. Continue adding the Plaster of Paris powder, tapping the sides of the container from time to time until the plaster powder reaches the top of the water as it is shown in Figure 77.
3. Finally, stir the mixture. Slowly stir the plaster of Paris mixture until it has a smooth consistency.

Figure 77. Plaster of Paris procedure pictures.

Casting application procedure

1. To measure the powder and water proportion in two different containers.
2. To mix both materials, adding the water to the alginate powder.
3. Desirably, to mix the mixture with a metallic spatula. If the setting-up time of your alginate is so fast, you can use a blender. In this case, the final mould will have a few bubbles, but it would not interrupt the result. Stop when the mixture starts to get a bit harden. It last around 60 seconds. The setting time can be controlled with the temperature of water used; a higher temperature speeds it up, while a lower temperature slows it down. The resultant mix should be creamy in consistency. [3]
4. Pour the mixture into the final container.
5. Cover the desired extremity or body part with Vaseline.
6. Introduce the desired extremity or body part inside of the alginate mixture.
7. Leave the extremity inside in a static position until the alginates stars to harden (around 3 min). By touching the mixture, it is easy to evaluate when to remove the extremity from the alginate.
8. Help the user to remove the extremity form the alginate already harden by pulling apart the alginate from his/her skin.
9. To pour gently the already prepared Plaster of Paris mixture into the alginate mould.
10. Let the mixture to set.
11. To wait a few hours (depend on the amount of material used). 2-4 hours. By touching the plaster of Paris, it is easy to evaluate when is dry enough to remove the alginate from the final mould.

DIARY RESULTS

Products used

- R&S Alginate Turbo Print Class A
- Scolacast powder
- Vaseline Original Pure Petroleum Jelly, 50ml

Depending on the setting time of your Alginate and Plaster of Paris brand and the amount of necessary material, different setting times are needed. It is recommended to practice with less amount of material and little shapes first to evaluate your materials without spending too much material and assuring future practices. For this reason, different samples were tried before casting the end user's hand. First, different experiences were done by casting a finger (a finger has less volume than a hand, so consequently less material needed). Table 17 shows comments and changes from one experience to the next one.

Figure 78. First samples. Finger casting.

Table 17. Finger casting experience

	1st Sample	*2nd Sample*
Alginate *Setting time and amount of material used*	Dental alginate A suggests: 18 grams of powder to 36 ml of water. Applying this proportion for a finger volume; **100 grams of powder to 200 ml of water**.	In literature was found; 100g of powder to 300 ml of water, we have tried to add 3 times of water per 1 part of powder. Final proportion used was; **75 g of powder to 300 ml of water.**
Results and Comments	Alginate mixture was so dense. **It hardened very fast.** *We got rid of it*	**Perfect density and creamy appearance were obtained.** It would be recommended to wait around 40s when the mixture is set in the future mould bucket, until introducing the desired body part to cast
Plaster of Paris *Amount of material used*	Ration 3/2 (powder /water) **200ml /133ml** **(powder /water**) Too much time was spent in the alginate procedure, so the Plaster of Paris hardened while preparing the alginate mixture.	Ration 3/2 (powder /water) **150 ml/100ml** **(powder /water)**
Results and Comments	*We got rid of it* (Much more volume than needed for a finger volume).	Good density and appearance. Almost perfect. A little bit less of water would be recommended.

When the proportions were set for a finger, and the procedure was known in a better way, the next step was to try with a hand. Unexpectedly, proportions and time settings changed when increasing the amount of material needed. Table 18 shows comments and results during the alginate casting at 2 casting experiences. Plaster of Paris comments were not described, because the proportions and indications were the same as for the finger casting experience.

Figure 79. Hand casting samples

Table 18. Hand casting experience

	1st Sample	*2nd Sample*	*3rd sample*
Alginate preparation	Increasing the amount but following the proportion used in 2nd finger casting example: 75 g of powder to 300 ml of water **325g of powder to 1300ml of water**	Coldwater in the fridge for an hour. 1450ml water 625ml alginate Blender mixed	Coldwater in the fridge for an hour. 3011ml water 1350ml alginate To use a little bit the spatula in the beginning Blender mixed
Results and Comments	Dust bubbles appeared. Not the creamy result we got with the last finger try because the volume was much higher. We got rid of it, it harden so fast.	Perfect. I recommend mixing a bit first with the spatula. Blender. And that's all. More material needed. A few bubbles had appeared due to the use of the blender, but it did not interrupt the function of final result of the hand mould.	Almost perfect. Good density. A few bubbles had appeared due to the use of the blender, but it did not interrupt the function of final result of the hand mould.

Appendix D

Sense 3D scanner Tech specs

Supported operating systems
64-bit Windows 8 or later

Scan volume
Min: 0.2m x 0.2m x 0.2m
Max: 2m x 2m x 2m
Dimensions
5.08(w) x 7.08(h) x 1.3(d) inches
12.9(w) x 17.8(h) x 3.3(d) cm

Operating range
Min: 0.2m
Max: 1.6m
Depth image size
640(w) x 480(h) px

Color image size
1920(w) x 1080(h) px

Field of view
Horizontal: 45°
Vertical: 57.5°
Diagonal: 69°

Spatial x/y resolution @ 0.5m
0.9mm

Depth resolution @ 0.5m
1mm

Operating temperature
10-40° C

Data interface
USB 3.0

USB cord length
6 feet

Maximal image throughput
30 fps

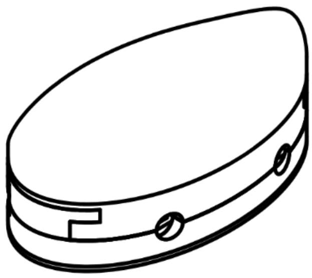
Hardware recommendations
Intel® Core i5™ 5th Gen or equivalent processor (click here for details)
RAM: 2 GB minimum
1280 x 1024 minimum screen resolution
4 GB available hard disk space

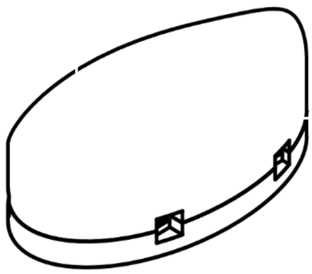
Warranty
1 year

Appendix F

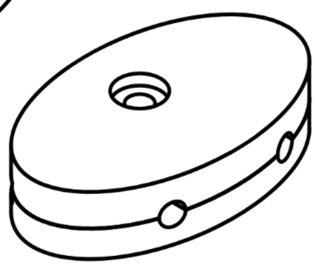
Technical draws and material description

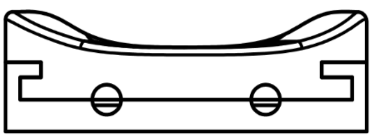
This module was conceived from the pre-concept HA1 and it is the central and main component of the bow holder. It has an oval shape and it is made up of 2 parts - a top part in contact with the user's palm and a bottom part assembled with the bow attachment module.

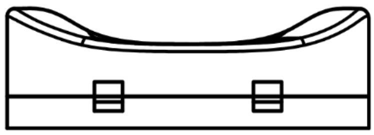




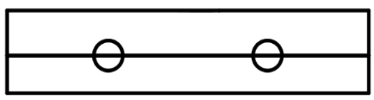
PALM SUPPORT

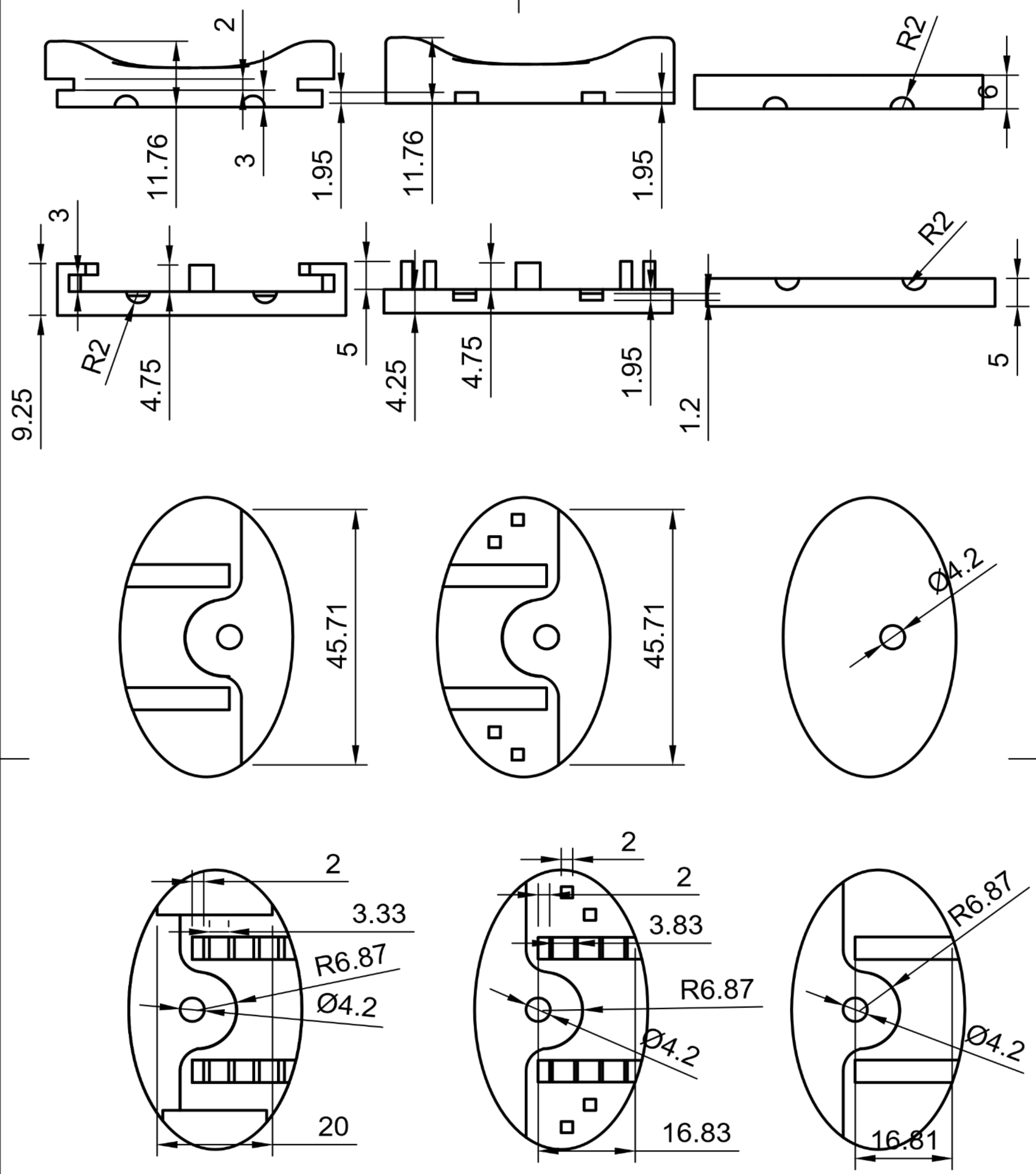






These two sub-modules are thought in this way to create an easy assembly mechanism with the hook and the thumb grip modules. The hook goes through a cylindrical socket in the bottom palm support component, so the post on the palm support can stick through and be attached to the Hook.





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		Title **Palm support2**	DWG No.
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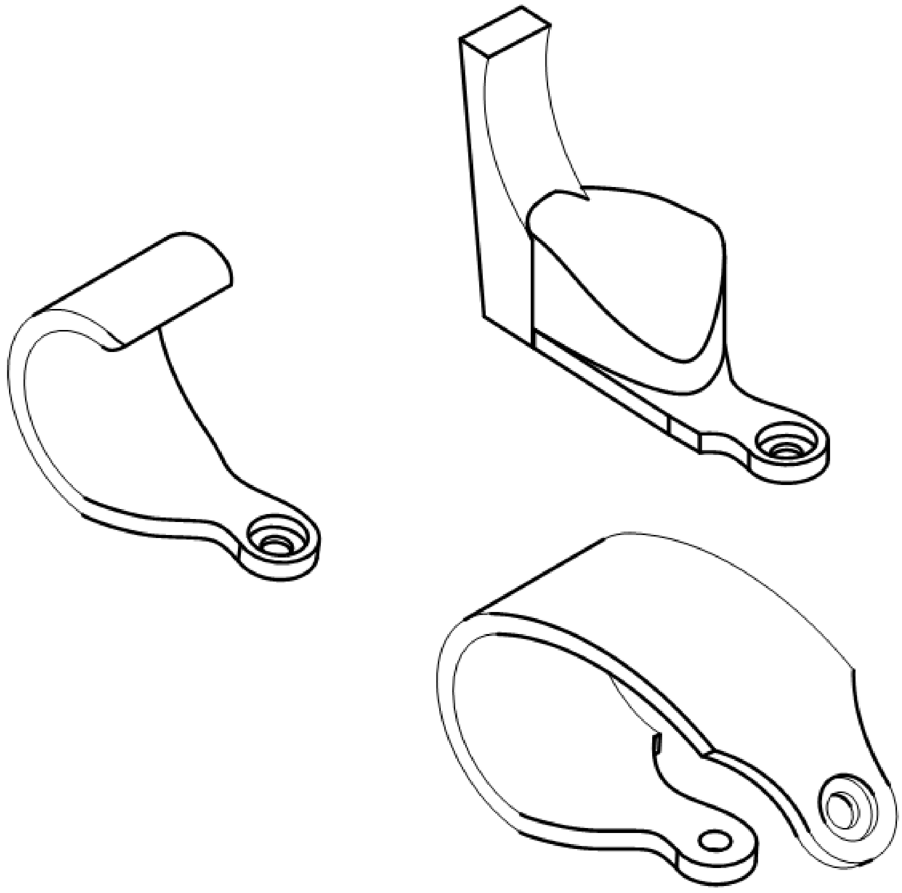
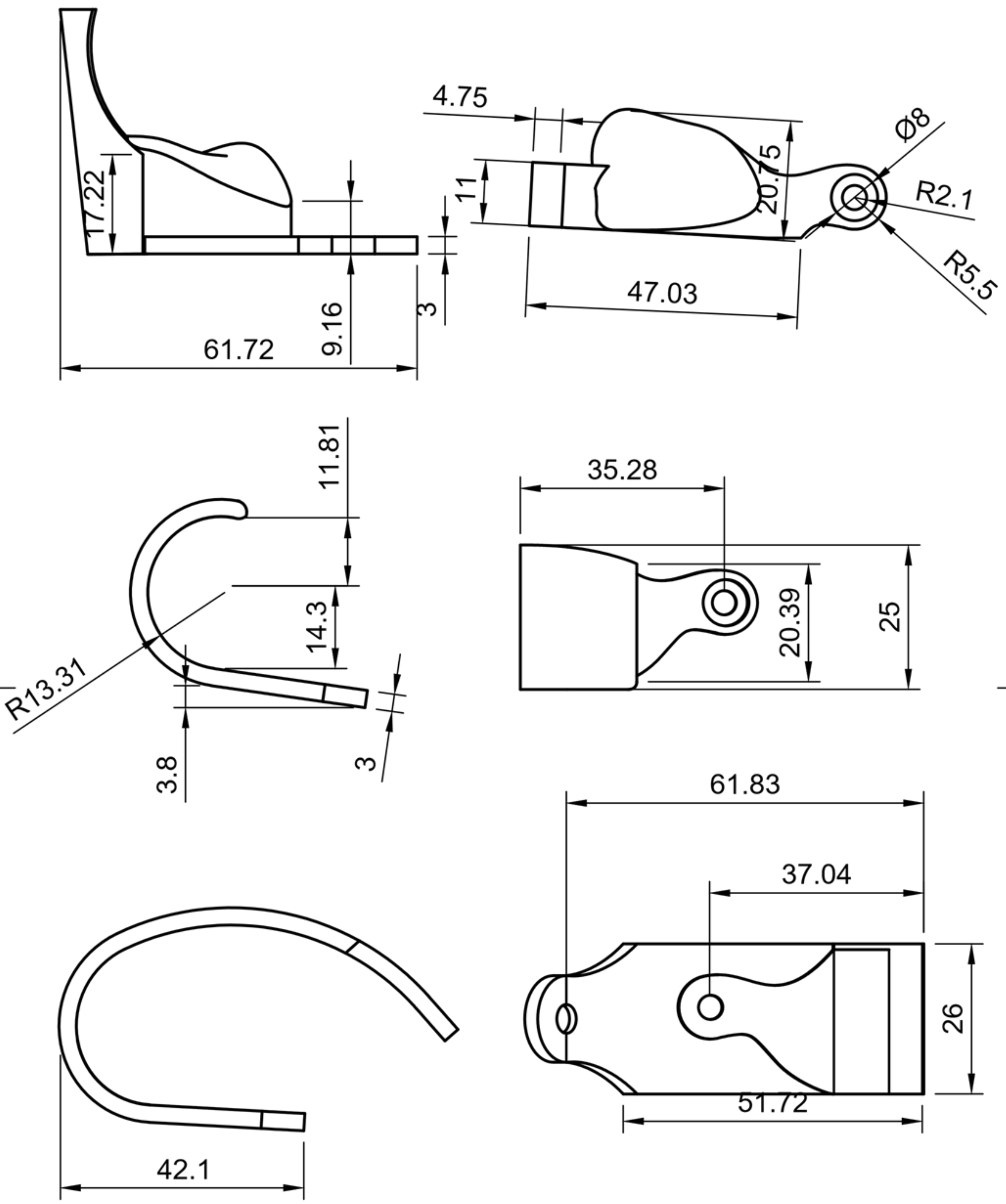
HOOK

Hook shape piece to support and hold the user’s pinkie. At the same time, this piece restricts the pinkie movement and corrects the wrist angle in relation to the bow.





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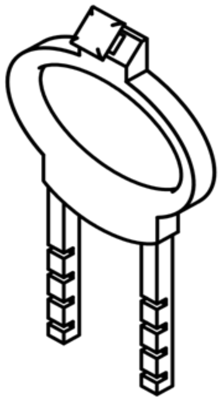
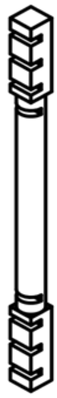
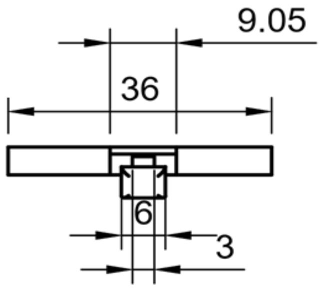
		Document type: Technical Draws. Bow holder	Document status
		Title: **Hook**	DWG No.
			Rev. / Date of issue / Sheet: 1/1

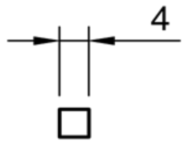
The objective of this module is to encircle the user's thumb and involve the current thumb sensitivity and movement in the act of bowing. Moreover, by gripping the thumb we add another point of support into the bow holder. The thumb grip is attached to the palm support from its right side by using a press fit mechanism reinforced by 4 notches. The user can adapt the length from the thumb grip by assembling it from notch number 1 to number 4.

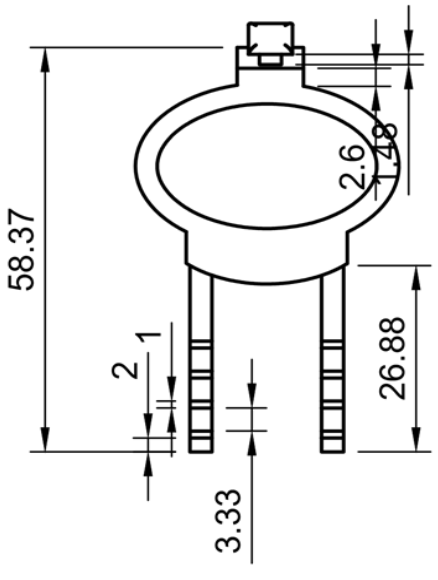
THUMB SLOT

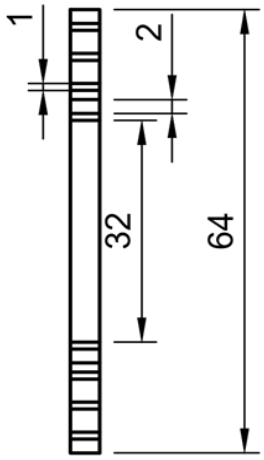












Dept.	Technical reference	Created by Clara Rionda Rodriguez 13/07/2019	Approved by		
		Document type Technical Draws. Bow holder	Document status		
		Title Thumb slot	DWG No.		
			Rev.	Date of issue	Sheet 1/1