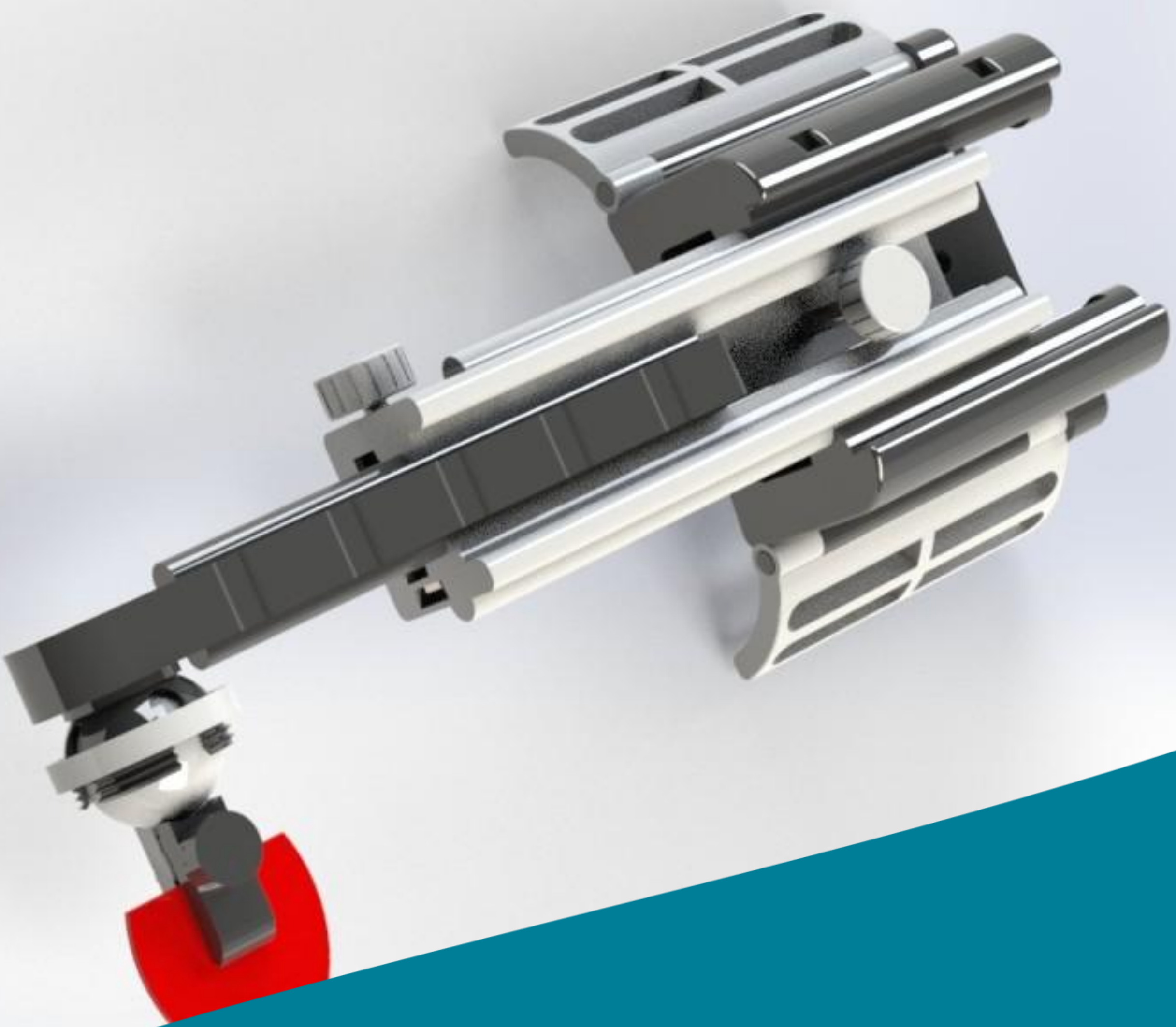

Design of a non-anthropomorphic passive adjustable upper limb 3D printed prosthesis for playing acoustic guitar

MSc Biomedical Engineering thesis

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TU Delft

Design of a non-anthropomorphic passive adjustable upper limb 3D printed prosthesis for playing acoustic guitar

By

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Index

Abstract

Background: Commercially available upper limb prostheses for playing guitar require professional assistance for proper fitting and usage. For people who lack this opportunity, alternatives are offered as research models or open-source models. However, adjustable models still require fitting assistance while parameter adjustment is extremely limited. This limits the user's ability to play more complex music.

Goal: This project proposes the design of a low-cost passive adjustable 3D printed upper limb prosthesis for people with no access to professional prosthetic assistance.

Methods: Both design and evaluation methods were applied. Regarding design, early concepts were designed and selected using a Morphological table and Harris profile, applying rapid prototyping for initial comparison. Regarding evaluation, a parameter measurement and a device functionality test with users with and without upper limb differences were performed.

Results: The final model was successfully printed using Fused Deposition Modeling. The model was evaluated via parameters measurements and a user device functionality test. Results showed that the device allowed the user to put the elbow as a reference point to aid mental mapping of the prosthesis. Speed and accuracy measured during the test suggest a positive outcome for end users.

Conclusion: This design presents an accessible and reliable solution for users with upper limb differences who want to improve their guitar playing skills without the need of professional assistance.

Key words: Upper limb prosthesis, acoustic guitar, passive, adjustable, 3D printing

Acknowledgments

First, I want to thank God for the accomplishment of this goal.

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Juan Pablo Alvarez Romero
Delft, 2025

1 Introduction

1.1 Upper limb differences

Upper limb differences correspond to malformations of an upper limb due to diverse reasons, including trauma, congenital or infectious/vascular diseases [1]. It was reported that in 2017, almost 60 million people worldwide suffered from limb loss due to trauma, with almost 12 million corresponding to unilateral upper limb trauma [2]. Lower limb amputations are on average 75% more frequent than upper limb amputations [3]. Nevertheless, upper limb amputations represent a challenge for activities of daily living (ADLs), which translates in an enormous impact on the user [4]. ADLs include activities such as dressing, writing or cooking. Fig.1 shows different types of upper limb amputations. Each type of amputation has different implications, since prosthetists must adapt the design of a prosthesis to the user's remaining range of motion (ROM).

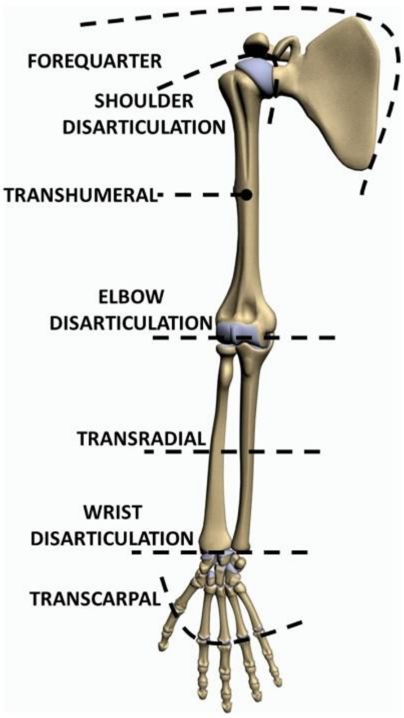


Fig. 1. Different upper limb amputation levels [1]

Among upper limb amputations, the most common types are transcarpal, transradial and transhumeral, respectively [5]. These can then be further divided into specific subgroups. For instance, transradial amputation is further divided into long, medium, short or very short residual limbs. Each of these subgroups influences which orthopedic solution will be advised. The shorter the residual limb, the more difficult it is to control a specific movement, and the greater the assistance required to be able to return to perform ADLs. And not only for carrying out activities, but amputations also hinder the person to community participation and social development [6].

Apart from amputations, congenital upper limb deficiency also has an impact on a person’s quality of life. This refers to malformations at birth. Congenital deficiency is mostly present in children rather than adults [7], since trauma is the leading factor of amputation among adults. It is reported that congenital differences take place in a 0.2% of live births [8]. These differences are classified into transverse or longitudinal, which are further divided into several other subgroups depending on the specific condition [9].

1.2 Categorization of upper limb prostheses

Prostheses are medical devices that replace body parts. There is a wide range of upper limb prostheses available, depending on the user’s needs. Different research groups throughout literature have diverse proposals on how to categorize the different types of prostheses [1, 4, 10]. Fig. 2 shows the different subgroups, using examples from the references mentioned. The diagram summarizes only upper limb prostheses, as lower limb prostheses can have a different approach on how to make a distinction between them.

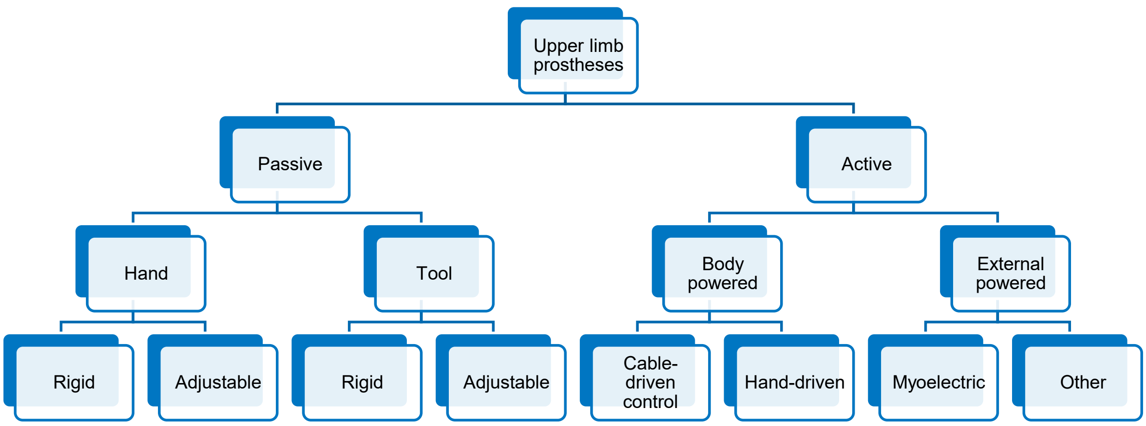


Fig. 2. Upper limb prostheses subgroups

Passive prostheses correspond to models that allow limited movement. These models are divided into hand or tool, which are further divided into rigid or adjustable. The main difference between these two groups is that models from the first group are desired to be anthropomorphic (i.e. human-like), whereas tools models focus on performance rather than a similar appearance to a human hand. Rigid models correspond to cosmetic-related solutions, where the user’s goal is merely aesthetical. Adjustable models allow the user to perform ADLs or to perform a particular task or hobby. Hence, activity specific prostheses (without internal powering mechanisms) are included in the prosthetic tool’s subgroup. Examples of these models vary for different activities, such as playing music or practice diverse sports. In addition, activity specific prostheses are being increasingly reported for being used with additive manufacturing technology, since it is a viable, accessible and low-cost solution for users who lack professional assistance for prosthetic manufacturing and fitting [11]. Literature recommends including the change of parameters on activity specific prostheses such as length, angle or rotation, depending the activity [12].

Active prostheses are internally powered, e.g. by motors or cables. As a trade-off, these models are increased in weight, cost and maintenance care. Body powered versions rely on the user providing the necessary force to move the mechanisms. Externally powered are complex models (such as the myoelectric models), since they have EMG sensors in the user's skin to detect signals sent to the muscles. These signals are interpreted into an electrical signal and allow the prosthesis to move accordingly. For comfortable use, prostheses and sockets should be tailored for a user. In other words, professional assistance (e.g. prosthetist) in the developing and fitting of the model is reported as very important [10, 13, 14]. However, despite its relevance, assistance is not always available due to factors such as cost, time or distance. Hence, it is reported that accessible and practical models are available for this target population [15].

1.3 Prostheses for playing guitar: patents & state of the art

1.3.1 Patents

Some examples of registered patents for upper limb prostheses for playing guitar can be found in Fig. 3. The first example shows a prosthetic attachment for stringed instruments. This model works using a cable and two metal rods to assist the user when playing the instrument. On the other hand, the second model is a prosthetic guitar pick attached to the distal part of the residual limb. Unlike the previous model, this device uses a guitar plectrum to allow the user to play the guitar. In the patent application it is stated that this device is intended for wrist amputation or some lower arm disability.

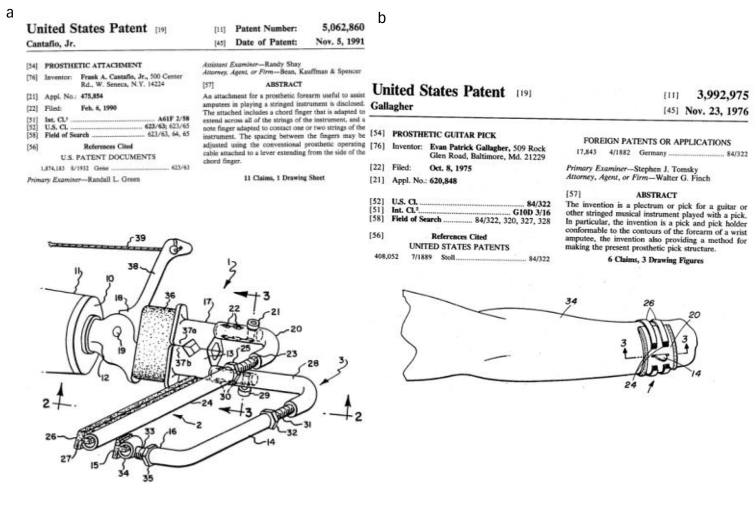


Fig. 3. Patents of prostheses for guitar playing: (a) Prosthetic attachment [16] & (b) prosthetic guitar pick [17].

1.3.2 Commercially available models

Several companies design, develop and manufacture different types of musical prostheses. In the specific case of the guitar, Fig. 4 shows three examples of companies that develop their own products and are commercially available. The three companies are TRS Prosthetics, De Hoogstraat Revalidatie and Koalaa Prosthetics. Different mechanisms are proposed to allow the user to strum the guitar strings and to play with essential movements, such as ball and socket or rotating duck. All these models count with angle-adjustment mechanisms.

The model presented by De Hoogstraat (the Netherlands) explores an innovative solution for users who do not want or need a prosthetic socket (connector part between user's residual limb and prosthetic terminals). TRS (USA) and Koalaa (United Kingdom) emphasize in having one socket and different prosthetic terminals, depending on the intended use. All these models are passive, since active models increase the cost of the device as well as the weight and comfort reported in similar devices. In this case, all models rely on using a guitar pick (also known as plectrum) and some parameters can be changed, more specifically the angular position. Additionally, they are not only reported as acoustic guitar models, but in general for similar stringed instruments such as banjo, ukelele or electric guitar.

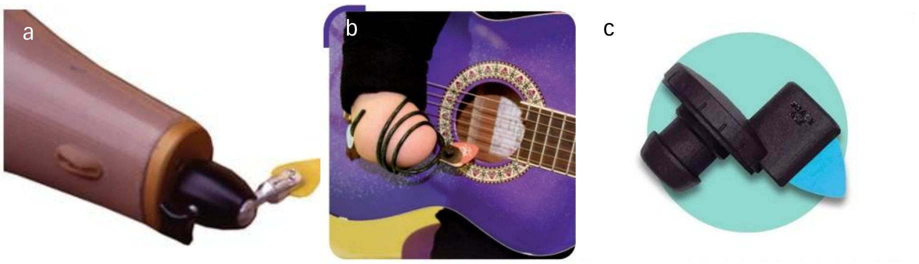


Fig. 4. Commercially available models: (a) TRS Prosthetics [18], (b), De Hoogstraat Revalidatie [19] & (c) Koalaa Prosthetics [20]

These models require professional assistance, since a socket must be manufactured or measurements are needed for fitting. Koalaa also offers sleeves for users with congenital upper limb differences, which is also an affordable alternative for users that have a long residual limb. In this case, De Hoogstraat works and offers models that do not require sockets and can be used without additional equipment, as shown in Fig. 4b.

1.3.3 Literature & open-source models

Besides the models that can be acquired via a specialized company or rehabilitation center, there are various research groups and designers who explore different alternatives to current commercially available products. They emphasize the need for accessible models. Some of them focus on designing a device for a specific user, whereas a more general use is also explored. The different designs are shown in Fig. 5. These models seek to take advantage of how 3D printing is becoming more accessible and capable of providing low-cost solutions.

Most of the designs include or use a guitar pick, since it is a reliable way to ensure the user can play properly the instrument. All the designs (except for Fig. 5d) were designed for one specific user: their research describes methods of obtaining the user's limb measurements such as scanning or manual measurements that allow the user to feel more comfortable when using the prosthesis. The open-source model is reported as adaptable to different users, hence the straps systems. However, the downside is the lack of adjustable parameters present in the rest of the designs.

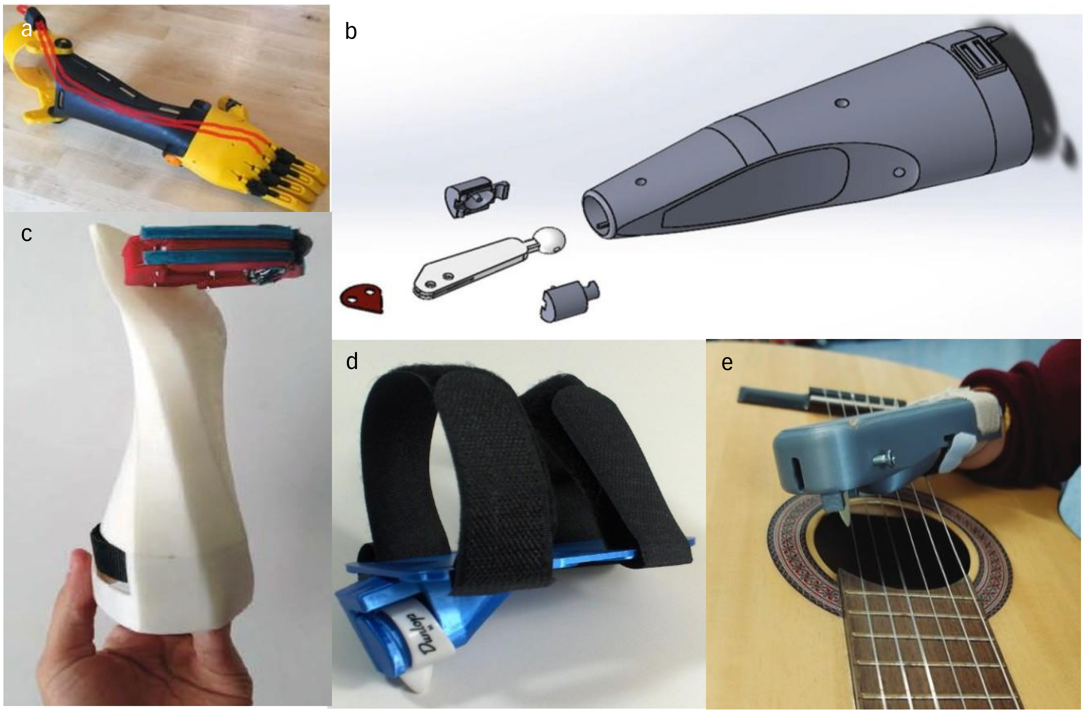


Fig. 5. Prosthesis for playing guitar reported in literature and open-source: (a) 3D printed hand [21], *(b) forearm 3D printed prosthesis* [22], *(c) upper limb prosthesis* [23], *(d) open-source design by Nate Munro* [24] *& (e) multi-activity prosthesis for children* [25]

As mentioned above, 3D printing has been widely used for designing low-cost alternatives not only for music prostheses, but also for general use or other activity specific examples [12, 26]. Additionally, there is an open-source online community called Enable [27], where designers upload the files necessary to print a prosthesis. 3D printing is divided into several specific types of additive manufacturing, but Fused Deposition Modeling is considered the most popular one due to its accessible advantages.

1.4 Theoretical framework

1.4.1 Acoustic guitar and plectrums

The acoustic guitar has 6 strings, each of them corresponding to a specific note when correct tension is applied (E, A, D, G, B and E, from low to high notes). The strings material includes nylon or metal, depending on the user's preference. Nylon strings are softer and easier to deform, whereas metal strings are not only more difficult to deform, but the sound is also more powerful. Different string material depends also on the intended music genre. Classical Spanish guitar is known for nylons strings, whereas rock is played with metal strings [28].

To play the instrument, a common alternative is the use of a guitar pick. The dimensions of guitar picks vary between different styles and techniques. Diverse sizes, material and widths can aid the user to accomplish specific sounds [29]. Large plectrums are suitable for conventional strumming. Small versions are recommended for fingerpicking, e.g. jazz. Common materials include plastic with several subtypes including nylon and acetal. Metal is also commonly used.

1.4.2 Guitar playing levels

Guitar playing levels are often divided into beginner, intermediate and advanced. However, these terms are subjectively used for everyday purposes. In order to accurately divide the playing levels, the format offered by The Royal Conservatory of Music is recommended, as its global reputation entitles as one of the most globally respected academies for music [30]. There are 11 levels, from Preliminary to Level 10. These levels are divided into three groups as follows:

- Elementary (Preliminary – Level 4)
- Intermediate (Levels 5 – 8)
- Advanced (Levels 9 & 10)

Each of the groups evaluates skills such as memory playing, technical playing (scales, patterns), ear tests and sight reading. Each level asks for more speed while playing the required melodies. In addition, *études*[1] increase in difficulty and complexity of movements (similar level description is listed by The Associated Board of the Royal Schools of Music, which is another highly recognizable music institution).

1.4.3 Guitar playing parameters

Speed, posture and accuracy are fundamental concepts when playing guitar. Each one of these concepts allows the user to interpret effectively a musical piece. If one of these elements is missing, the outcome might not be as intended. In this context, speed corresponds to maintaining the appropriate tempo specified in a music sheet.

Complementing speed, accuracy translates into playing the correct note as specified in the music sheet. Although there is no clear consensus in literature on the percentage of right notes considered on a basic or advanced player, guitar playing certifications rely on an approximate distinction between levels. Together, the application of these concepts allows the guitarist to play the right note at the right time. For this, good posture increases the probability for the user to play as intended. The range of motion for guitar playing was recommended between 30° and 45° [32]. A wrong posture can lead to discomfort, muscle tension or an impediment to playing appropriately. Additionally, good posture involves playing with the forearm resting on top of the guitar, having the elbow as a supporting point [33]. For advanced players, it is expected to have a proper posture, speed while playing and accurate performance without looking at the hands, since it represent stress for the eye and can lead to distraction [34]. In addition, time and practice are crucial for the improvement of the user to play properly the instrument. Expert players transmit not only measurable parameters while playing, but the intrinsic value and feeling that can communicate with the public present.

[1] Musical composition intended to improve the user's playing skills [31]

1.4.4 Elbow biomechanics

The elbow works as a pivot point that allows the arm's movement. Fig. 6a shows the elbow joint as well as the muscles and bones that are connected to it. As shown, there are three main bones that hold together the joint, starting with the humerus and connecting to the ulna and radius. Muscles are also shown to highlight their importance. People with upper limb differences below the elbow still have their muscles, which work as an additional aid to perform ADLs. This is not the case for other types of upper limb differences, such as transhumeral. Finally, ligaments and tendons keep muscles and bones connected, such as the anterior band or the biceps tendon. This allows free range of motion (ROM), which include flexion, extension, pronation and supination [35]. These movements allow the rotation of the arm for the completion of diverse tasks.

The length of the residual limb establishes the degrees of freedom for pronation and supination available (see Fig. 6b). People with long or medium length remaining limbs can have still 100° or 120° of rotation respectively, whereas people with short or very short residual limb lack this movement. This hinders people from rotating the arm when playing an instrument, even if a prosthesis is being used. Elbow flexion allows movement from 0° to 145°, but between 30° and 130°, functional movement for ADLs can be found [36].

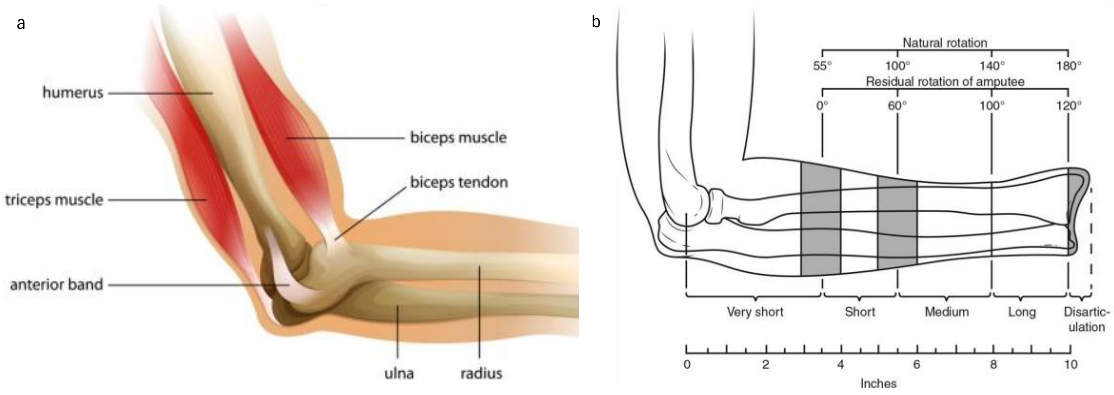


Fig. 6. Elbow joint: (a) muscles, tendons and bones in the elbow joint [37] & (b) difference in residual rotation in upper limb amputees [38]

A schematic representation of the elbow joint is shown on Fig. 7. The model describes the flexion of the arm and the parameters acting on it. The three joints (S=shoulder, E=Elbow and W=Wrist) are shown in circles. By analyzing the movement, the variables that must be taken into consideration are the distance of the arm (d), the angle between the arm and the pivot point (θ) and the torque (τ) that is generated in the elbow. When flexing the arm, the biceps contracts and the triceps expand, allowing for the musculoskeletal system to perform the movement. Based on this, the relationship between the muscle and the torque at the elbow is affected by the muscle's length and mechanical advantage [39].

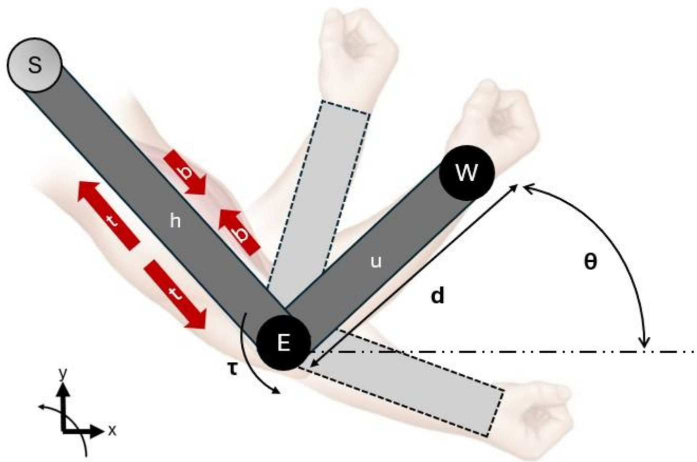


Fig. 7. Biomechanical representation of elbow flexion: S = shoulder, h = humerus, E = elbow, b = bicep, t = triceps, u = ulna, W = wrist, τ = torque, d= distance, θ = angle (adapted background image from [40])

1.4.5 Feedback system

Feedback in a system is crucial. Without it, the user does not know the status of the activity as well as its performance. Hence, a control loop showing how a passive prosthesis for playing guitar is shown in Fig. 8. This is represented under the assumption that the user is not applying visual feedback while playing. The user's arm exerts force that is transferred with the prosthesis to the guitar strings with a flexion/extension movement. Since this device is passive, no sensor is used to provide feedback. Instead, feedback is returned when, for instance, the elbow is working as an anchor point on top of the instrument and the deformation of the strings while strumming. Additional input is the auditory feedback, which allows the user to know if the tone is sounding as expected. Visual feedback would benefit the system, but this would not allow the user to sight reading when playing a more complex music piece.

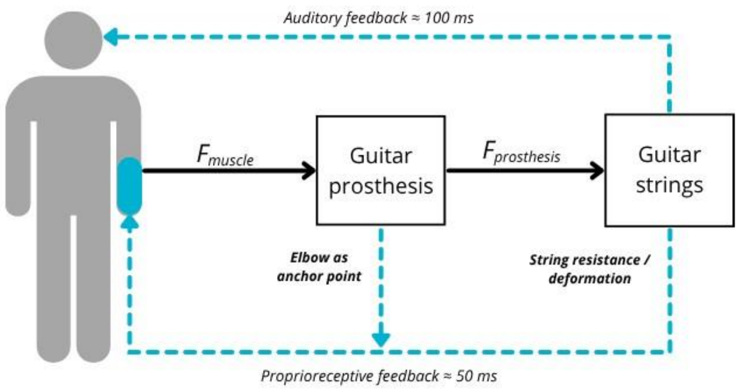


Fig. 8. System's control loop: the force applied from the user transfers to the guitar strings which are then deformed, providing both auditory and proprioceptive feedback to the user

1.5 Problem statement

For users with below-elbow differences, one of the most common methods to play acoustic guitar is using the activity-specific upper limb prostheses. For users who do not have access to a professional prosthetist for assistance in their community, alternative models are offered in both literature and open-source 3D printing communities. However, current models do not provide sufficient assistance to improve the user's playing skills. For that reason, users are limited to basic movements and have no assistance in continuing learning more complex skills such as sight reading while playing and increased speed. To address this issue, an adjustable 3D printed upper limb prosthesis would allow users to have the possibility to improve their guitar playing level while not having the need for professional prosthetic assistance.

1.6 Goal

To design a passive adjustable prosthesis for users with below-elbow differences for providing freedom of movement when playing acoustic guitar. This enables the user to perform guitar playing according to the Royal Conservatory of Music standard. A prosthesis will be 3D printed for functionality evaluations, which includes a parameter measurement evaluation for angle, length and don/doff validation and a functionality user test to corroborate with technical requirements as well as performance criteria.

2 Methodology

2.1 Approach and perspective

The *User-Centered Design* approach [41] was chosen as the general project's approach. This method gives an emphasis on the user's needs, which are crucial for an adequate design. The steps that integrate this approach include:

1) Front end user research
2) Define
3) Create
4) Prototype
5) Evaluate use

The first step involves research to identify a gap or problem in a specific situation. Techniques used in this step are oriented to getting to know better the end-user and having a complete overview of the current solutions made for the problem of interest. Based on this, a clear and specific objective is defined, which corresponds to the second step. This will establish clear directions to the project. The third step corresponds to creating and proposing solutions based on the information collected in the two previous steps. This solution must fulfill both technical and performance needs. After establishing viable solutions, the concepts are further developed in different levels of detail to establish which concept will be worked on in its fullness. This step allows researchers and users to better understand the device's performance before having a final model, which involves both time and money. The fourth step corresponds to working on the concepts and final model.

Finally, the last step is related to validating the final solution with the established requirements and performance criteria. This is done via different types of testing and measurements. The goal is to determine if the device's performance solves the established problem. Further steps could be made past this point depending on the nature of the researcher (a company might further develop and sell the product, or a researcher might publish the results). By having a specific approach, the whole process follows a series of interrelated steps towards solving a problem.

The project was planned according to the previously mentioned phases. A specific timespan was dedicated for each phase, and most of the phases were interconnected or working in parallel. In total, the project was divided as follows:

- Phase 1: Analysis phase
- Phase 2: Direction Phase
- Phase 3: Design phase
- Phase 4: Development phase
- Phase 5: Evaluation phase
- Phase 6: Presentation phase

This report is mainly divided into two major chapters: Model Design and Model Evaluation. Each one of them has different subsections describing their methods, results and interpretation. The Model

Design chapter (Chapter 3) discusses the overall process related to the model's design, whereas the Model Evaluation chapter (Chapter 4) discusses the evaluation phase based on the final model. Further descriptions are included in each chapter's subgroups to allow a more detailed and comprehensive read and understanding of the project. Protocols are followed in both chapters depending on their nature.

Moreover, this project is designed considering the perspective *Design for Sustainability* [41]. This perspective describes a set of rules known as the "The 10 Golden Rules of Design for Sustainability". It involves key points such as weight, energy (in terms of resource consumption), protection and toxicity. Regarding this perspective, weight (by optimizing model), upgrading (by allowing interchangeable parts and repair), protection (by having a robust design that can last) and construction (as few joining elements as possible) allow to think in a more sustainable way. This helps by working with ecological responsibility and not overseeing these crucial elements that make the product more attractive for both the market and users.

3 Model design

3.1 Methods

To design a prosthetic device that allows users to play acoustic guitar, a methodology must be followed to consider all necessary steps and their respective stakeholders. For this reason, the methods and strategies used in this project will follow recommendations based on the Delft Design Guide [41]. The design process was divided into three groups: Discover, Define and Develop & Deliver.

For the Discover section, interviews with end-users were conducted. These give the researcher a perspective on the user's opinion, motivation, past experiences with similar products or how the current problem was being solved. Following TU Delft's safety protocol, the university's Human Research Ethics Committee (HREC) approved the application to conduct these interviews (ID 5375). Requirements, needs and wishes are also shared by the interview participants to provide a complete perspective on the problem but also their point of view. Including the user at early stages of the project is crucial and advised for products which are intended to be patient tailored [42]. In addition, a problem definition using the 5W1H technique was used, as well as a list of requirements and performance criteria. This translates a written problem into different measurable points to later validate the design.

Afterwards, the Define section included using a Morphological chart to explore the sub-functions of the device. This tool allows to explore different solutions to a specific problem, which are later analyzed. At this point, the emphasis is to propose not only conventional ways to solve a problem, but to propose creative solutions. Then, a Harris profile was used to establish which of the designs fulfilled better the performance criteria. This is based on a four-segment score, which helps to visually determine the optimal approach. Finally, in the Develop & Delivery section, the selected concept was worked out in detail. After choosing the most promising model, 3D physical models were used to assess the design. To provide a wider perspective of the situation, the Product usability evaluation technique was used to test and validate the corresponding device.

3.2 Results

3.2.1 Concept exploration – research and interviews

To propose a concept, it is important to know more about the specific problem and background. This initial research reveals gaps in literature or commercial products. Initial research was performed to find models and necessities among users with upper limb prostheses for playing acoustic guitar. Some of the results were already mentioned in the Introduction chapter.

Referring to research, an emphasis was recognized in the need of having parameter-changing options in activity specific prostheses [12]. This research group exemplifies how three different activities (sport, music and hobbies) were benefited after the used prostheses were applied with modifiable parameter adjustments. Recommended parameters include length, angle or rotation, depending on the specific task. Furthermore, referring specifically to playing acoustic guitar, two research groups highlighted the importance of working on the current models so that improvements can be achieved [22, 23]. Moreover, a research group present various designs for low-cost devices focusing on children, and combining the advantages of additive manufacturing with specific activities [26].

These findings are complemented by online interviews, where voluntary participants share their experience, recommendations and feedback on having prostheses for playing musical instruments. Two participants were interested in sharing their experience. The interviews had the following structure:

- Experience with guitar playing or other stringed instruments; type of upper limb difference
- Temporary solutions prior to current prosthetic device
- Current challenges
- Most important aspects to consider regarding the device
- Feedback

Participant 1 (female, 60 years old) has a transradial amputation due to an accident. She shared that prior to the accident, she was involved with musical instruments. Currently she plays ukelele, pan flute, piano, violin and a type of banjo. In other words, music has been an important part of her life. To be able to continue to play music, she tried to use pedals, but it wasn't a viable solution since it became a demanding task. After playing the pan flute for a while, a prosthetist made a prosthesis for her to play the violin. However, this became also problematic, which led to requiring physical therapy. Eventually, she found out about a guitar prosthesis (so she could be singing while playing), and the manufacturers adjusted the device specifically for her so that she can feel comfortable while playing. She has several prostheses for different activities. Since some models for playing music are too heavy, she does not use them.

Currently, she finds it difficult to play complex chord arrangements in stringed instruments (guitar, ukelele), to mentally map the prosthesis (since no anchor point is available for assistance) and fingerpicking is demanding since visual feedback is always necessary. When she tries to play without looking at the strings, the wrong note is hit, which becomes annoying for her to play. All these challenges make her stuck in learning. Eventually she did not want to play anymore. Regarding the most important aspects for a prosthesis for guitar playing, weight and comfort were the main points. As an additional aspect, she wished for the design to aid her to be more accurate while playing.

Participant 12 (male, 17 years old) has a congenital deficiency in his left hand. He shared that his involvement with music is profound. He plays the piano (almost for four years), produces music, works with audio engineering and plays some drums. Apart from this, he is also a composer, which helps him submerge in the world of music. Regarding acoustic guitar, he tried it out for a short period of time by himself, but decided not to continue since only strumming was possible for him. He shared that every time he wanted to learn a song, he needed to find another way to interpret it, because some chords were difficult for him. He adjusts the music he wants to play, rather than adjusting the instrument.

He has a prosthesis for playing the drums, since guitar adjustment was not helpful. The main reason was that the plectrum was far away from the strings. Hence, he prefers to use the right hand to play the chords. It is difficult for him to fingerstyle, so he only uses the strumming technique. After playing for a long time, it becomes uncomfortable for his left hand. For him, lightweight and allowing transpire are two key components regarding a prosthesis for music. If it interferes when playing, he will not use it. It also needs to allow playing for a long period of time.

3.2.2 Concept exploration – technical requirements

Based on the experience and input from the end-users in the interviews and key recommendations from research, a list of technical requirements and performance criteria was proposed. This is a basis for the project since they will be validated on the final model. The list of technical requirements goes as follows:

1. The device should be able to change its **length** (at least 15 cm and up to 20 cm).
2. The device should be able to adapt to various forearm **widths**.
3. The device should be able to change the **angle** perpendicular to the device (between 0° and 45°).
4. The device should be able to adapt various **sizes** of guitar pick (small, medium and large).
5. The device should be **lightweight** (up to 300 gr).
6. The device should be able to be **don/doff** by the user itself with no additional assistance.
7. The device should allow the user to **sight reading** while playing acoustic guitar.
8. The device should be **strong** enough to withstand string strumming.
9. The device should be **3D printed** using Fused Deposition Melting (FDM)
10. The device should allow conventional **range of motion** (ROM) while playing acoustic guitar

As well as performance criteria:

- Cost-effective
- Durability
- Ease of adjustment
- Ease of assembly
- Ease of interchangeable parts

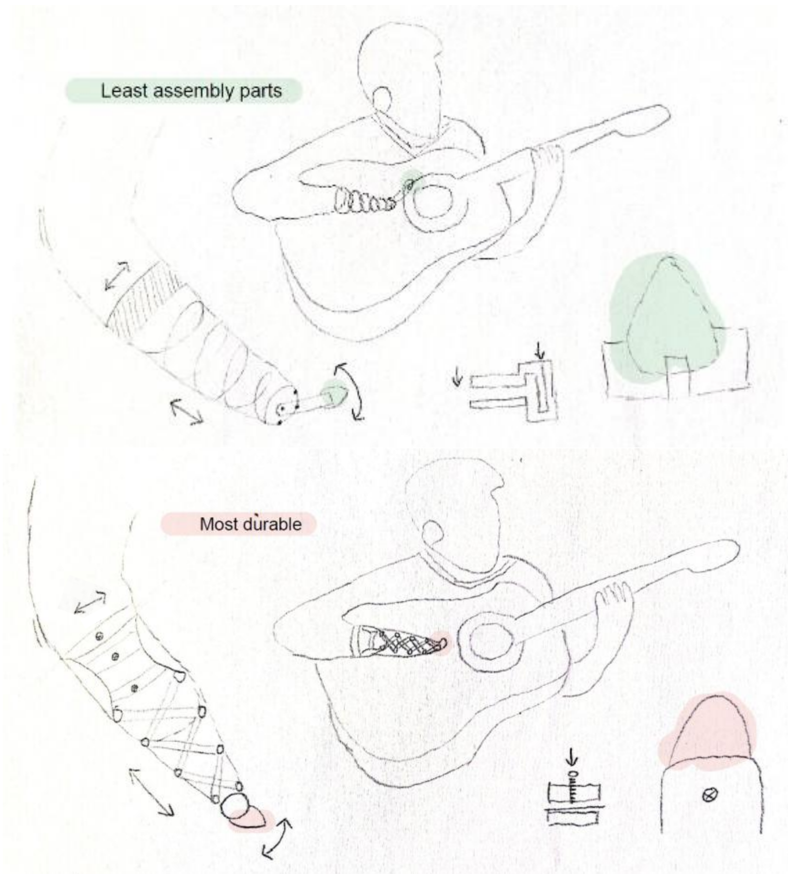
3.2.3 Concept generation and selection

This section has the intention to generate different ideas that are aligned with the requirements and performance criteria. A common technique is the Morphological table. This table (see Appendix A) describes subfunctions within the system and different ways to solve those subfunctions. Three main paths were selected: Least assembly parts (green), most durable (red) and most lightweight (blue). To have a clear visualization of each of these concepts, sketches were done to fulfill this. These sketches are shown on Fig. 9. Four main mechanisms are proposed: length, angle, forearm attachment and plectrum attachment (i.e. guitar pick attachment).

The first concept (least assembly parts) proposed a telescope-like mechanism to extend and retract depending on the distance between the user's stump and the guitar box. If the plectrum is not placed in this position, then the sound will not sound strong enough. Here, the attachment to the arm is completely covering the forearm and allowing the plectrum to adjust in the horizontal direction via reference points. Finally, to avoid using more material in the connecting part, the plectrum would stay in position using normal and friction force.

The second concept (most durable) emphasizes making the device as reliable as possible, rather than focusing on the number of parts. The length mechanism would still allow movement to get close to the guitar box, using a scissor-like mechanism. The angle mechanism would allow more degrees of freedom than the previous concept due to a ball and socket system. The attachment to the forearm contains screws and side connecting elements to properly place it in position and make it stable. The plectrum would also have a screw to impede movement while playing.

Finally, the third concept (most lightweight) explores a solution with minimal material usage without compromising the functions of the device. The extension mechanism is inspired by drawer length mechanisms. Instead of using screws, the preferred mechanism would be a snap fit mechanism with lightweight printed parts. The plectrum would be relying on a torsion spring acting as a clamping mechanism for plectrum insertion and extraction.



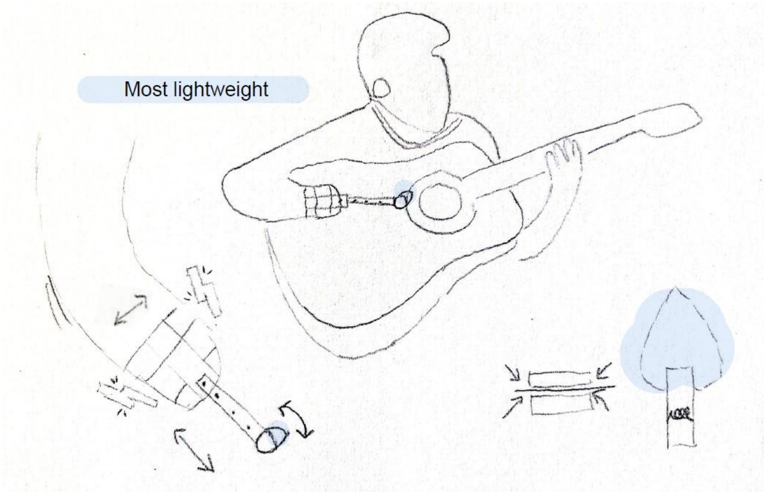


Fig. 9. Sketches of the three concepts: (Top) Least assembly parts, (Middle) most durable & (Bottom) most lightweight (image inspired by drawing designed by Freepik [43])

After a proper analysis of the concepts, a selection process was conducted. The technique used for this step is Harris Profile, shown on Fig. 10. In this case, the table is aligned with the established performance criteria. There are four parameters to evaluate, starting with the lowest score: (- -), (-), (+) and (++). If the parameters include double sign, red and green boxes are used to provide visual clarity in decision making. To properly assign value to each concept, the sketches were used as input to analyze how the performance criteria is being fulfilled. The three concepts were not completely prototyped since the time factor was short to build and compare various prototypes. Instead, the best solution is the one that was worked on detail.

Performance criteria	Concept **1**: **Least assembly parts**				Concept **2**: **Most durable**				Concept **3**: **Most lightweight**			
												
	--	-	+	++	--	-	+	++	--	-	+	++
Cost-effective			■		(red)	(red)					(green)	(green)
Durability	(red)	(red)					(green)	(green)		■		
Ease of adjustment			(green)	(green)			■				■	
Ease of assembly			(green)	(green)	(red)	(red)					■	
Ease of interchange-able parts			■			■					(green)	(green)

Fig. 10. Harris Profile comparing the three concepts: Least assembly parts, most durable and most lightweight

As seen in Fig. 10, Concept 2 appeared as the least fulfilled concept, having cost-effectiveness and ease of assembly as the main negative points. Both Concepts 1 and 3 had strong points in ease of adjustment, ease of assembly, cost-effectiveness and ease of interchangeable parts respectively. However, Concept 1 is designed in a way that the printed parts might not be strong enough to withstand too frequent length changes. Hence, Concept 3 appeared as the best solution. Moreover, changes could be made to this concept to improve the negative points and that are positive points in other devices. In other words, a hybrid solution between the three concepts but having Concept 3 as the main body. This approach was chosen as the optimal design.

3.2.4 Concept improvements

Once the concept is selected, 3D physical models were used to properly develop the model. Rapid prototyping gives the researcher an idea on how viable a concept is. The concepts must be sufficiently worked on so that a clear idea and conclusion about whether to continue or not can be made. This has the advantage of working with clear ideas but at the same time not wasting time trying to fix problems that might not be necessary in the first place.

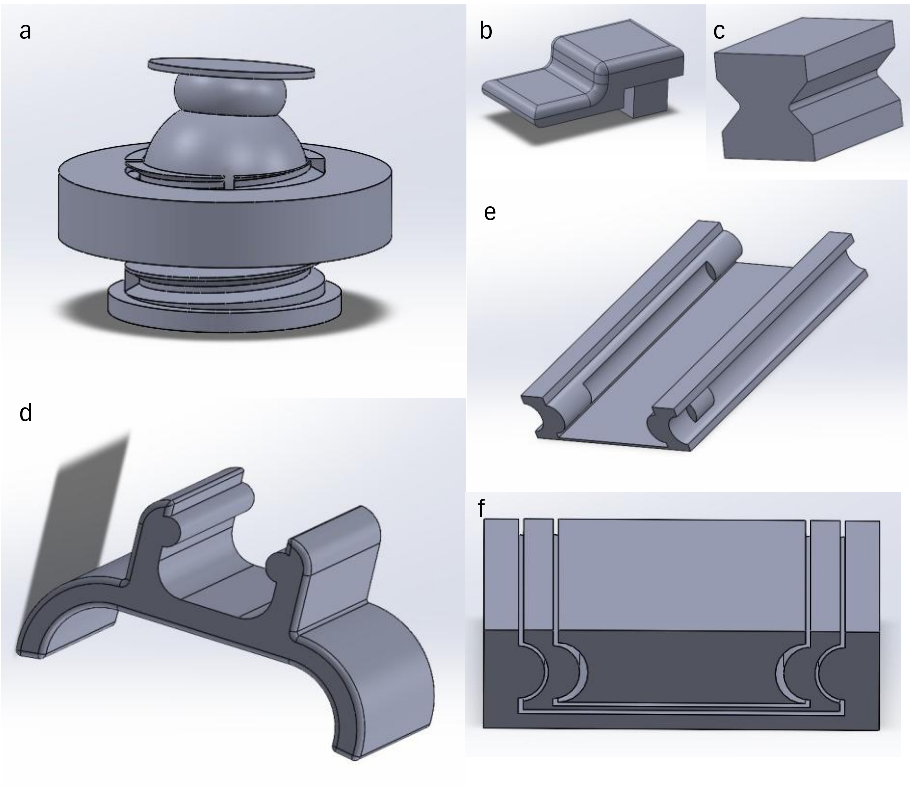


Fig. 11. 3D models in prototyping phase as proof of concept: (a) angle mechanism, (b) plectrum gripper, (c) length beam shape, (d) forearm attachment, (e) alternative for length beam, (f) option for length compact beams

The angle mechanism proof of concept (PoC) shown in Fig.11a represents the idea of having a ball and socket system that allows the user to change the location of the plectrum as desired. In comparison with the other approaches, this can facilitate movement and does not necessarily involve the use of separate tools such as screws and nuts. The plectrum gripper (see Fig. 11b) concept works with the friction and normal force to attach the plectrum, so it does not move. To complement this design a bottom half would be required. At the same time, Fig. 11c, Fig. 11e and Fig. 11f explore different topologies on how the length mechanism could look like. A sliding mechanism could be optimal for the user to extend or retract the system, depending on the distance of the residual limb. Finally, Fig. 11d dives into a design where the base of the length mechanism is attached as one single piece. This idea would minimize the use of multiple assembly parts. Straps could go around the forearm to stabilize the system.

Some of the models were printed to visualize in a more detailed way. Fig. 12 shows the printed parts. It can be seen how the length mechanism was explored to have different shapes to compare friction and if the shape allows smooth transitions. As seen, printed screws were tried so that metal screws could be avoided. It was found that they were prone to break since the user needed to frequently change position. An alternative to the ball and socket was to have a different angle-shift mechanism (as shown in Fig. 12b) working with screws. It was concluded that the friction found in the ball and socket system was appropriate to solve the problem without additional tools. Fig. 12c shows different boards to measure the sizes of balls and holes. It was found that an optimal size play was to have the printed parts 0.2 mm smaller than intended to allow some printing errors or material inflation that would later cause a problem. This was tried out for the screws, ball system and nuts holes. This is also the case for Fig. 12d and Fig. 12h. Fig. 12e (adhesive Velcro) and Fig. 12f (flexible Velcro) show the initial proposal for attachment to the forearm. A brace that could attach to the upper arm was not considered as the elbow and part of the arm is intended to be resting in the guitar. Finally, Fig. 12g, 12j and 12i explored different topologies and shapes for the length system and the angle joint.

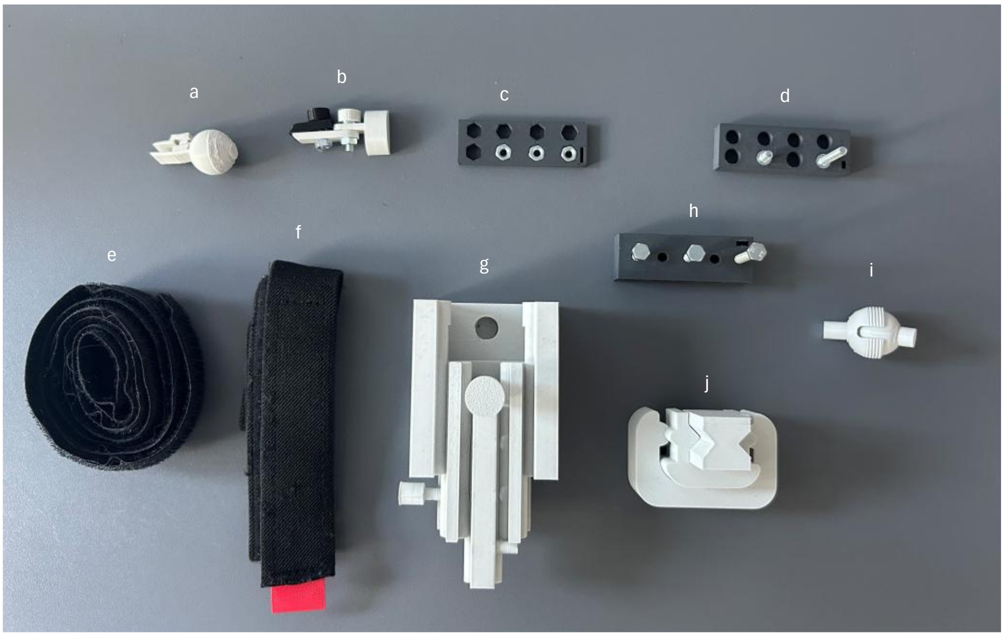


Fig. 12. Prototyping designs: (a) Ball and socket system with no screws for plectrum grip, (b) angle adjustment mechanism for horizontal position change, (c) nut-size board, (d) screw head size board, (e) adhesive Velcro strap, (f) flexible Velcro strap, (g) early prototype for length mechanism, (h) screw size board, (i) ball and socket system & (j) alternative approach for length mechanism

3.2.5 Final model

Finally, Fig. 13 shows the final design obtained. SolidWorks 2023 (Education License) was used to design the model. It includes three different mechanisms: length, angle and attachment. This last mechanism is further divided into plectrum attachment and forearm attachment. These mechanisms were chosen to allow the user to move freely while playing and comply with the technical requirements and performance criteria.

The length was established between 15 and 20 cm since other prostheses worked on similar distances [44]. The final model consists of three modules: Base, Middle and Top. These allow for different lengths depending on the user's preferred position. The Base module has side wings that work as hinges to adapt to various forearm widths with the use of Velcro straps. For this, printed rods were used to connect them as they stay indefinitely in that position without being moved. The Middle module is connected with a screw in a vertical way to the Base module and in a horizontal way with the Top module. At the distal point of the Top module, a ball and socket system is responsible for having the plectrum in a specific position. The socket has a 20.2 mm inner diameter and 23.2 mm outer diameter. The ball has a 20 mm diameter, which allows it to be moved freely in the socket if no pressure is applied. For this, a ring with 22.2 mm inner diameter and 27.2 mm outer diameter is used to tight the ball and socket and firmly lock a position. The socket and ring are threaded, meaning the tightening and loosening movement is smooth. In addition, all the circular holes have a diameter of 4.2 mm for M4 screws. The holes for the nuts have a hexagonal end cut to allow the nut to slide into the hole and stay in a desired position. The Top module can be placed either facing left or facing right. This function is added to be accessible for both right and left-handed users.

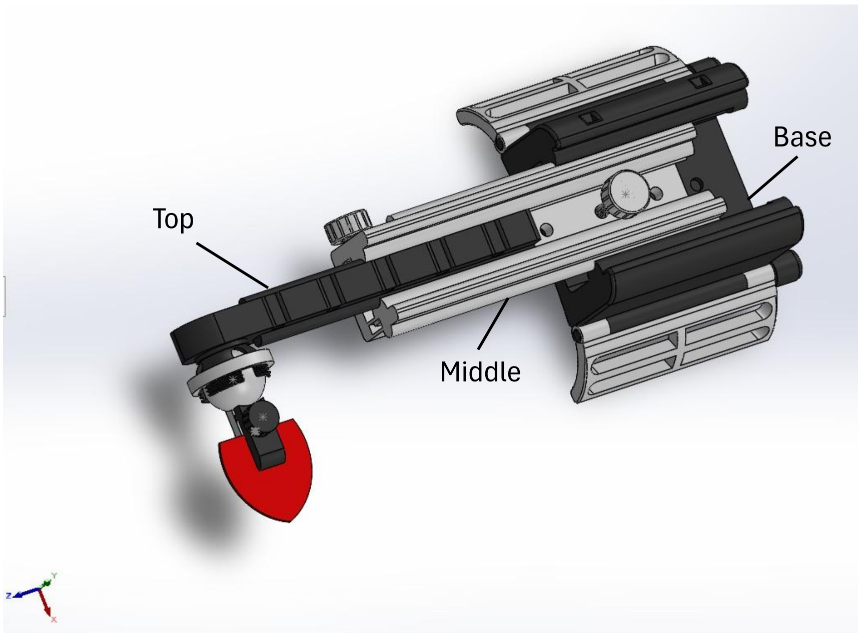


Fig. 13. SolidWorks view for the final model. The three main modules are shown in the image: Base, Middle and Top.

The SolidWorks model was then printed with FDM and later assembled. The only post-processing needed was to remove the support structure. It is recommended to leave the printed parts for several hours before assembly, since with time the parts expand slightly. If not, the length mechanism and the holes are slightly reduced in diameter, which leads to difficult assembly. The position of the device in a user's residual limb is represented in Fig. 14. It was noted that the model had some vertical displacement when playing the strings, which required tight adjustment to the forearm. The following parameters were used to print the final design:

- Material: Polylactic acid (PLA)
- Printer: Bambu Lab X1 Carbon
- Orientation: vertical
- Support: tree
- Infill density: 20%
- Pattern: Gyroid
- Wall thickness: 2 mm
- Nozzle size: 0.4 mm
- Speed: between 200 and 300 mm/s depending on layer
- Temperature: between 190°C and 240°C for the nozzle and 65°C for the bed
- Time: approximately 8 hours for multicolor printing and 5.5 hours for unicolor printing

Parameters such as orientation of parts are essential for proper printing. To print the modules, if the piece is printed in a horizontal way, then the strength of the piece is high, but the quality and detail of small parts decreases. On the other hand, placing the piece in a vertical way allows for higher quality in printing with less strong properties. This is because of the properties of the filament when being printed in parallel to the printing plate. Another example lies in the material, which is an important factor when considering establishing printing costs [45]. Polylactic acid (PLA) is a common material for this purpose and has adequate mechanical properties, in contrast with materials such as thermoplastic polyurethane (TPU), which is used in flexible applications. PLA is widely used as biomedical 3D printed material due to biocompatibility and versatility [46]. The speed of printing and the thickness of walls and layers play also an important role, since strength and quality must be high to obtain a durable design.

Fig. 14. Final model attached to user's residual limb and elbow resting above the guitar.

3.2.6 Model analysis

Eq. 1 was used to obtain the center of mass, where m stands for mass, r for distance and M for the total system's mass. The system is regarded as a discrete system. Calculations were made in the x axis as well as in the y axis. The center of mass aids to analyze where the system's average weight is found. This changes when the device is extended or reduced.

$$CoM = \frac{\sum m_i r_i}{M} \quad \text{(Eq. 1)}$$

For the system to be in equilibrium, the forces and moments involved must equal zero (see Eq. 2 and Eq. 3). For this, a free body diagram helps to visualize the forces acting on the system. Fig. 15 shows how the device's weight is being pulled down. To counter this force, the straps around the user's forearm exert normal forces F_{N1} and F_{N2}. The distance a and b correspond to the distance between the center of the straps and the reference point marked with a red mark. Eq. 3 shows the moment created between the straps. The fact that the straps are as far away as possible from each other makes the system more stable. However, when the user is playing guitar and the strings get in touch with the device, an external force is experienced. This is shown in Fig. 16 and 17. The first example considers the force when playing from below. Here, F_{N3} is mostly counteracting the force of the string. This is the case for F_{N5} when the force is coming from the opposite direction. The proximity to the reference point, the length to the external force L and the distance between the straps are key to maintaining equilibrium (see Eq. 4, 5, 6 & 7).

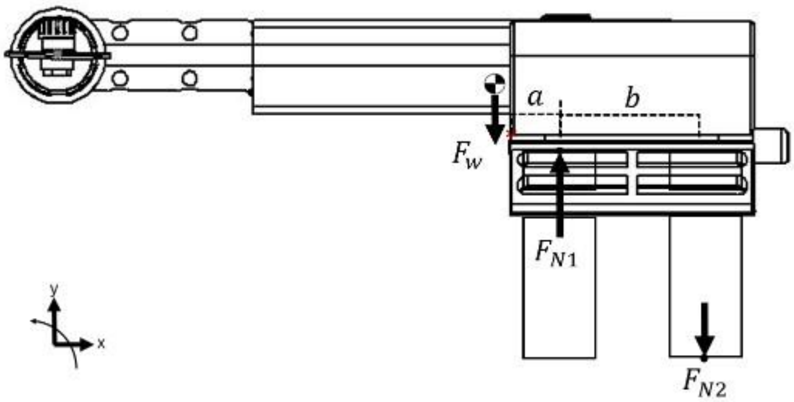


Fig. 15. Lateral view from the model with straps attached and free body diagram, with the reference point marked in a red. a is the distance between F_{N1} and reference point, whereas b is the distance between F_{N2} and the strap next to the reference point

$$\sum F_y = 0 \quad \text{(Eq. 2)}$$

$$F_w = F_{N1} - F_{N2}$$

$$\sum M_o = 0 \quad \text{(Eq. 3)}$$

$$F_{N1}a - F_{N2}(a + b) = 0$$

$$F_{N1} = \frac{F_{N2}(a+b)}{a}$$

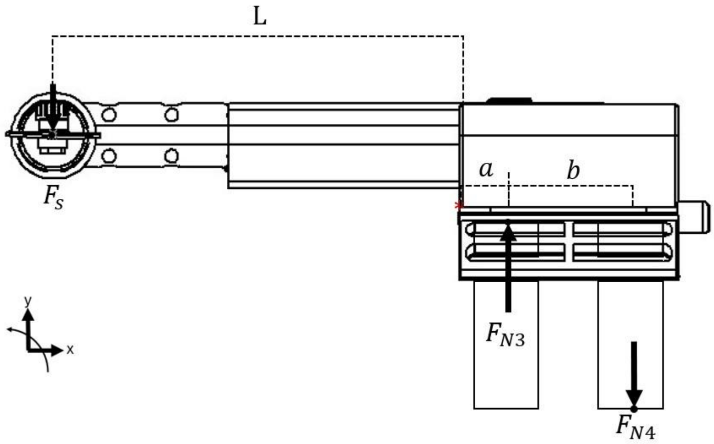


Fig. 16. Lateral view from the model with straps attached and free body diagram, with the reference point marked in a red, where F_s corresponds to the string's force, L is the distance between reference point and force, a is the distance between F_{N3} and reference point & b is the distance between F_{N4} and the strap next to the reference point

$$\sum F_y = 0 \qquad \text{(Eq. 4)}$$
$$F_{N3} = F_s + F_{N4}$$

$$\sum M_o = 0 \qquad \text{(Eq. 5)}$$
$$F_s L = F_{N3} a - F_{N4}(a+b)$$

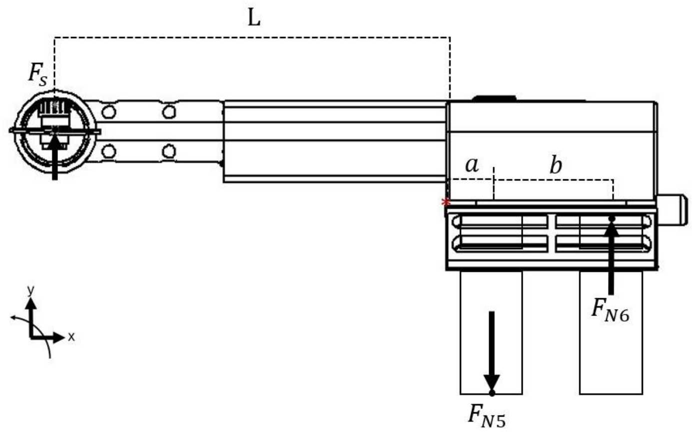


Fig. 17. Lateral view from the model with straps attached and free body diagram, with the reference point marked in a red, where F_s corresponds to the string's force, L is the distance between reference point and force, a is the distance between F_{N5} and reference point & b is the distance between F_{N6} and the strap next to the reference point

$$\sum F_y = 0 \qquad \text{(Eq. 6)}$$
$$F_{N5} = F_s + F_{N6}$$

$$\sum M_o = 0 \qquad \text{(Eq. 7)}$$
$$F_s L = F_{N5} a - F_{N6}(a + b)$$

Since the normal force from the forearm's contact and the device is the only force counteracting the weight of the model, this attachment must be as stable as possible. The fact that the skin is being used as the attachment point makes the Velcro surrounding necessary to be tight, since the skin high deformation characteristics can hinder complete attachment. The longer the device is, the more deflection the system will experience, considering also the material properties and the location of the force. When considering the force acting on the strings, the base must be tight. If not, the length of the device and force applied will deform the device.

3.3 Interpretation of results

The device was successfully designed and printed using design techniques from literature. Each of these stages involved finding creative solutions for the specified problem. The interviews gave valuable input in the design and context of the problem. Using the elbow as reference point for a low-cost and accessible general model is something that raised the attention to both interview participants. The technical requirements and performance criteria established a proper basis for design and development. Different concepts and strategies were properly explored to make the design accessible and with as few parts as possible without compromising proper operation. Prototyping models were shown to explain the reason for arriving at the final model. In other words, indicating the design process.

The tolerances in the design allow for small printing errors. This benefits users with printers with low printing accuracy. Additionally, the bending on the device could be mitigated by some alternatives, such as an additional anchor point, lengthening the attachment to the forearm or reducing the total length that the device can provide. The try-out showed that the model worked successfully. However, this device works under the premise that the user can flex the elbow to strum the strings. Users without this possibility would not be able to use it. For instance, spastic users would not be able to perform these movements even if they meet the condition of length and residual limb.

4 Model evaluation

4.1 Materials and methods

4.1.1 Parameter measurements

Once the final model was ready, a validation and evaluation process to comply with the technical requirements and performance criteria was made. To have a complete perspective, two different evaluations were conducted: the first one consists of a parameter measurement evaluation, where the goal is to verify that the device performs as intended. To accomplish this, the following parameters were evaluated:

- Measurements
  - Length extension
  - Model weight
  - Angle variation
- Device strength
  - Model under load in different points
  - Use of diverse guitar plectrums
- Donning/doffing
  - Assembly time
  - Elements count

Fig. 18 shows the materials used for measurements and device strength tasks. Included in the materials used were a scale (Kern EMB 2000-0S with max. 2000g), a clamp, a slotted mass set of weights, the assembled model, a 30 cm long ruler (HEMA) and two guitar plectrums (Dunlop 0.73 mm and 1.5 mm respectively) additional to the one added in the final model (Dunlop 1.38 mm). The set of weights system consists of three weights of 100 gr each one, a 100-gr rod to keep the weights in place and the final model with 15% infill. In addition, the software Kinovea v. 2023.1.2 was used to measure the model's length and angle adjustability.

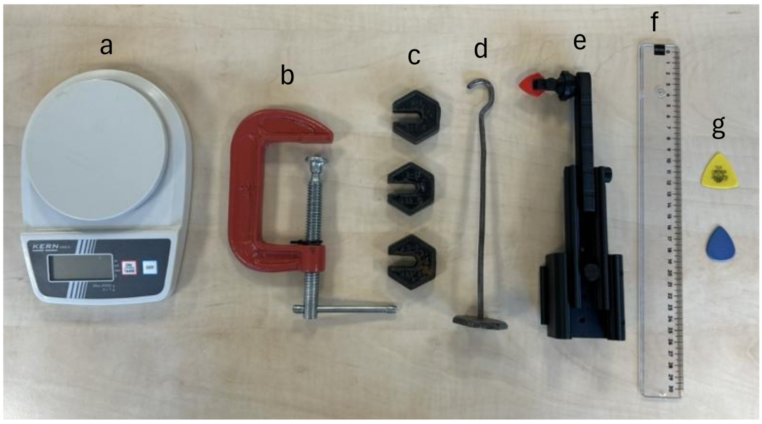


Fig. 18. Materials for parameter measurement: (a) scale, (b) clamp, (c) three 100 gr weights, (d) one 100 gr rod for the weights, (e) prosthesis without attachment mechanism, (f) ruler & (g) two guitar picks

Furthermore, to evaluate the donning/doffing activities, the final model and all the components were used. These tasks were performed using the researcher's dominant hand (right) to emulate the available hand from a user with upper limb differences. Even though other body parts (remaining limb, legs, trunk) were used to assist the activities, the affected hand was not used. The assembly task was performed three times to obtain an average on how much time is needed for the very first assembly. For posterior uses, the donning/doffing process is much faster since almost all the parts are already in place. Fig. 19 displays the components needed to assemble the final model. Since there are multiple parts, it is easier for the user to change something if it does not work anymore. The following elements list the assembly parts needed:

- 1x Base module
- 2x wings
- 2x printed rods
- 1x Middle module
- 2x sets of M4-30 screws and M4 nuts
- 2x printed knobs for the M4-30 screws
- 2x Velcro straps
- 1x Top module
- 1x ring
- 1x set of M4-12 screw with M4 nut
- 1x ball with lever
- 1x cover for lever

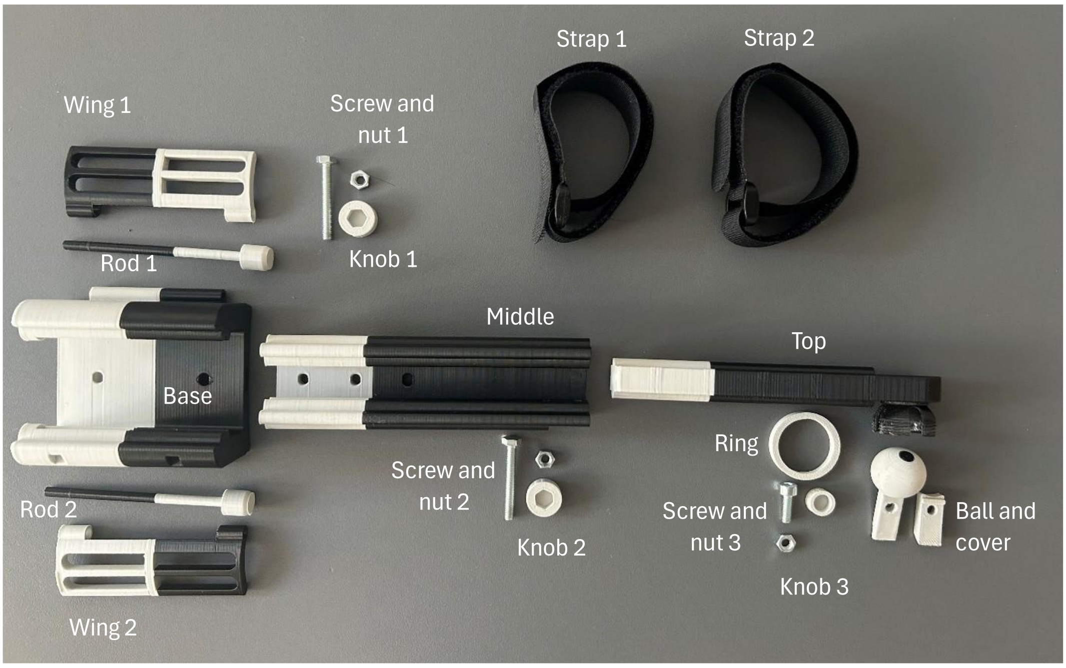


Fig. 19. Final model assembly components

4.1.2 User functionality test

The second validation evaluation was a device functionality test with participants. For this, voluntary participants with and without upper limb differences performed a series of tasks to assess whether the device fulfills the intended purpose. The inclusion of participants without upper limb difference is due to the unavailability of multiple participants with upper limb differences. No previous experience was required to take part in the study. First, the participants were asked to sign the Informed Consent Forms as required by the HREC protocol (ID 5649) and provide contact information. Then, the participants were asked to play a note pattern. Four different tasks were conducted based on this initial instruction. The tasks consisted in playing a pattern of notes for a short period of time with the help of a metronome to analyze the tempo:

- Task 1: Play the notes in the four tempos with visual feedback and elbow placed above the guitar.
- Task 2: Repeat previous task without visual feedback
- Task 3: Play the notes in the four tempos with visual feedback and with armpit above guitar, which leads to having the elbow without reference.
- Task 4: Repeat previous task without visual feedback.

The order of the notes was: E, G, B, *E*, B, G and E again (*E* corresponds to the note in the first string, which is the thinnest one). The four tempos used were 50, 70, 90 and 110 BPM. The remaining hand was asked to be played on the guitar arm. Users were asked to don the device by themselves with one hand. Task 1 and Task 3 were used for the participants to get used to playing with the prosthesis. Tasks 2 and 4 were used for the results section. The rules for evaluating the accuracy were the following:

- Task can be repeated if device is not properly adjusted
- Order of the pattern is for orientation only
- Clean notes count as one correct note.
- Accuracy is measured based on how many correct notes were played (i.e. 7/7 corresponds to 100% accuracy)

Then, a series of questions inspired by the Orthotics Prosthetics Users Survey (OPUS) questionnaire [47] were responded, as well as other self-created questions. The amount of time for length adjustment was measured. Finally, feedback was given by the participants. The response options for the OPUS questions were the following:

- Strongly Agree
- Agree
- Neither agree nor disagree
- Disagree
- Strongly disagree

The materials used for this stage include:

- An electro-acoustic guitar Yamaha CX-40
- The final prosthesis model
- Forms to fill out the results
- A cell phone camera used for taking pictures and recording users playing the guitar

4.2 Results

4.2.1 Parameter measurements results

The model's length was measured to adequately establish the extended configuration of the prosthesis with Kinovea. This is to help the user to reach different locations along the playing space, independently of the length of the residual limb. As seen on Fig. 20, the length is 26 cm. When the prosthesis is fully reduced, the total length is 17 cm. This reduced length is intended for users with long residual limbs who do not require to attach the device close to the elbow. The weight of the used model considering the plectrum is 93 gr. The model with all parts weighs 120 gr with 20% infill.

Fig. 20. Length validation on extended model

The device was then measured in terms of the degrees of freedom offered by the angle mechanism (ball and socket). This can be seen on Fig. 21. For this, five different positions were tried out: left, straight, right, facing down and facing up. As seen, this system allows multiple ranges of motion along the horizontal and vertical axis, since the ball attached to the socket can move freely.

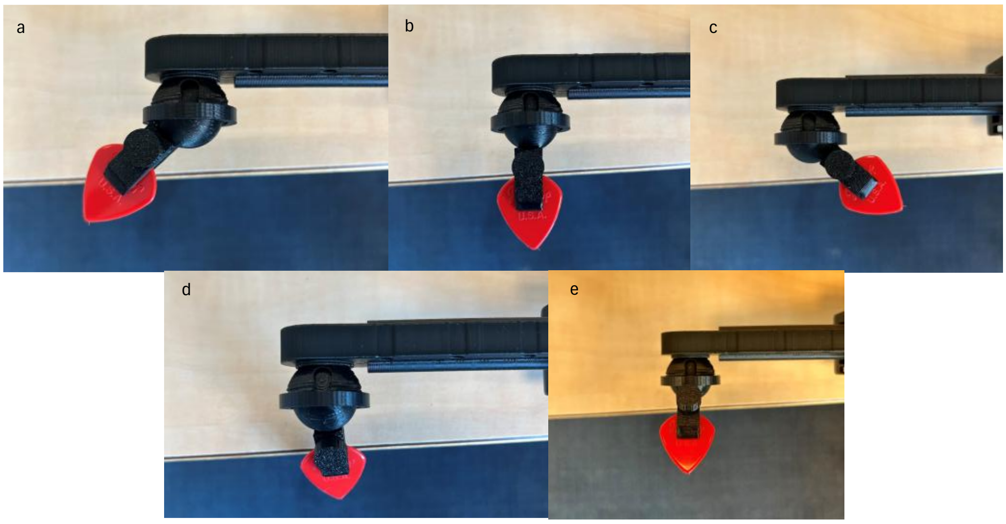


Fig. 21. Angle measuring validation: (a) left, (b) straight, (c) right, (d) down & (e) top view

As seen in Fig. 22, a reference line was established (measured by Kinovea) to properly measure the angle between the reference line and the tip of the guitar plectrum. The negative sign indicates that the angle is being measured from the left. This angle shifting can be complemented with the change of length of the device, allowing for multiple configurations that allow the user to play in a comfortable way.

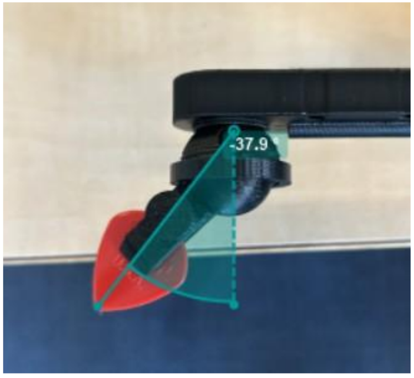


Fig. 22. Ball and socket angle configuration

Subsequently, the model was clamped to a table and applied to a mechanical load of 4 N (i.e. ≈ 0.4 kgf) to emulate strumming force [48], having the model in 24 cm in length. This condition is shown on Fig. 23. For this, two locations are used as contact points with the weights: first, in the most distal part of the device. Secondly, at the top of the plectrum, which is emulating hitting the guitar string from the bottom. Then, the same experiment was done but with a longer adjustment of 26 cm (see Fig. 24)

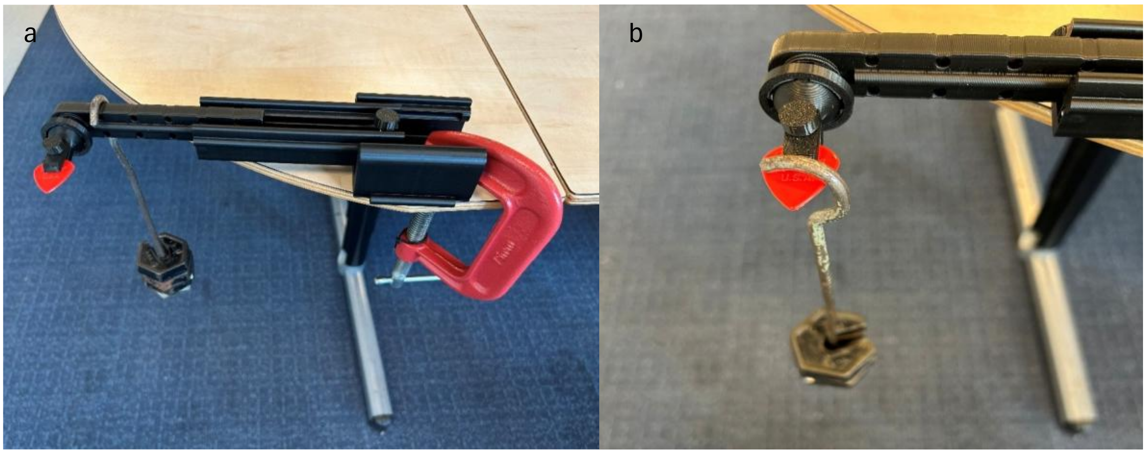


Fig. 23. Left: Model under load; Right: Model under load from the plectrum

Fig. 24. Model under load with 26 cm: (a) distal part & (b) on plectrum

Additionally, different sizes of plectrum were used with the same loading condition. This can be seen in Fig 25. The yellow plectrum is the largest plectrum used in the study, with 3.2 cm maximum length and 0.73 mm thickness. On the other hand, the blue plectrum is 3 cm large with 1.5 mm thickness. Finally, the red plectrum is Nylon 1.38 mm thickness with 2.5 cm length from point to point (made from a plastic called Delrin). As seen, all plectrums (regardless of thickness or dimensions) were able to withstand the load and maintain the desired position.

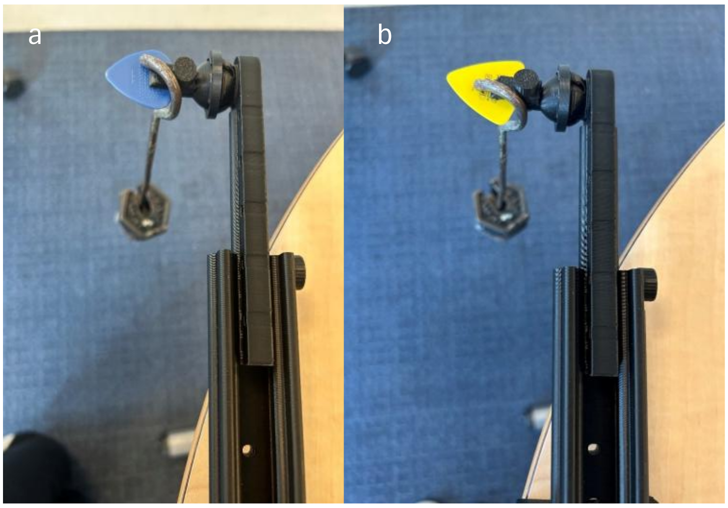


Fig. 25. Model under load: (a) with blue plectrum & (b) with yellow plectrum

Different positions for the plectrum were also evaluated. As seen in Fig. 26, three different positions were tried under mechanical load to maintain the ball and plectrum in position (left, top and right). This is to emulate the different positions that the user can choose while playing. As seen, both the plectrum and the ball system stay in the desired position when 4 N are applied, simulating the load while strumming the guitar.

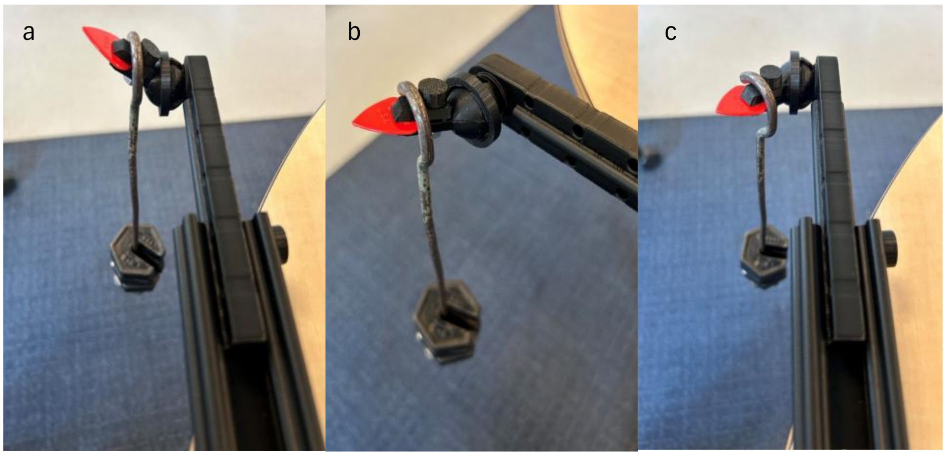


Fig. 26. Mechanical load: (a) oriented upwards, (b) oriented to the left & (c) oriented to the right

Finally, the parameters measurements evaluation finishes with the donning/doffing tasks (assembly times and elements count). There are in total 21 parts (six of them being screws and nuts), whereas the rest is 3D printed using FDM. The straps were bought locally and the screws and nuts were acquired from the Faculty Workshop. Moreover, Table 1 shows the three different assembly procedures done by the researcher. The whole assembly was divided into several phases containing different specific tasks. The first three phases involve the assembly of the section of the device that goes directly attached in the forearm, whereas the remaining phases involve the completion of the assembly. This includes assembling the plectrum holder, the ball into the socket and the Top module into the Middle module.

Phase	Time (minutes and seconds)			
	Assembly 1	**Assembly 2**	**Assembly 3**	**Average**
1) Base, rods and wings	1 min 42 sec	1 min 20 sec	1 min 50 sec	1 min 37 sec
2) Straps in device	3 min 27 sec	1 min 44 sec	1 min 15 sec	2 min 08 sec
3) Attach to forearm	2 min 26 sec	30 sec	29 sec	1 min 08 sec
4) Middle and nuts	2 min 50 sec	42 sec	37 sec	1 min 23 sec
5) Rest of assembly	6 min 07 sec	8 min 45 sec	3 min 11 sec	6 min 01 sec
Total	**16 min 34 sec**	**13 min 03 sec**	**07 min 24 sec**	**12 min 17 sec**

Table 1. Assembly time of the device measured three times

4.2.2 User functionality test results

Eleven participants were able to take part in the device functionality test. 55% of participants were male and 45% female. The average participant's age was 27.8 years old. 90.9% of participants reported to be dominant in the right hand. 36.3% of participants reported to have some kind of experience with playing stringed instruments, such as acoustic guitar or ukelele. Out of the eleven participants, one participant reported upper limb difference (trauma, transradial amputation). Fig. 27 shows the participant with the prosthesis attached to the arm, whereas Fig. 28 shows another example of the device placed in a participant's forearm. For participants without an upper limb difference, it was asked for them to place the wrist facing down to avoid using the hand as support.

Fig. 27. Device functionality test results of Participant 1: (a) playing the notes with elbow placed on top of guitar & (b) elbow moving freely

Task 1 (elbow support and visual feedback) was the easiest reported task to complete, with 63.3% of participants choosing this option. The second easiest task was Task 3 (no support, visual feedback), with 45.4% of participants choosing this option. Between the tasks without visual feedback, Task 2 (elbow support) was preferred according to 45.4% of the participants. Task 4 (no support) was reported as the most difficult task to complete for 63.3% of the participants. By comparing these two last Tasks, Task 2 reported a mean in accuracy for 62%, 66%, 69% and 58% for 50, 70, 90 and 110 BPM, respectively. Task 4 reported 61%, 52%, 60% and 61% of accuracy for 50, 70, 90 and 110 BPM, respectively. Median values for Task 2 at the different tempos were 57%, 71%, 71% and 57%, whereas Task 4 reported 71%, 57%, 57% and 71%. Finally, the mode for Task 4 corresponds to 86%, 71%, 43% and 57%, with 71%, 57%, 71% and 71% obtained for Task 4. All participants responded that they felt they would improve their performance with more practice.

Fig. 28. Device functionality test results of Participant 7: (a) playing the notes with elbow placed on top of guitar & (b) elbow moving freely

Participant's accuracy for Task 2 can be graphically seen in Fig. 29. The horizontal axis corresponds to the four tempos used during the test. The vertical axis corresponds to the accuracy percentage obtained. Raw data for the graphs can be seen in Appendix B. Fig. 30 shows the participants accuracy for Task 4. 100% accuracy was achieved by 50% of the experienced players and 28% of the inexperienced players

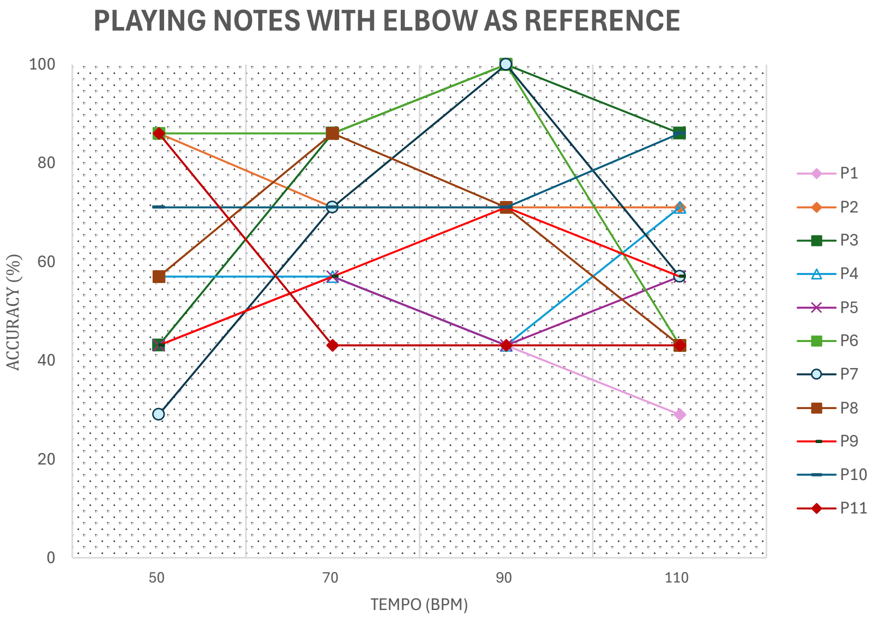


Fig. 29. Participant testing results: participants were asked to play the seven notes at four different rhythms with elbow placed above the guitar.

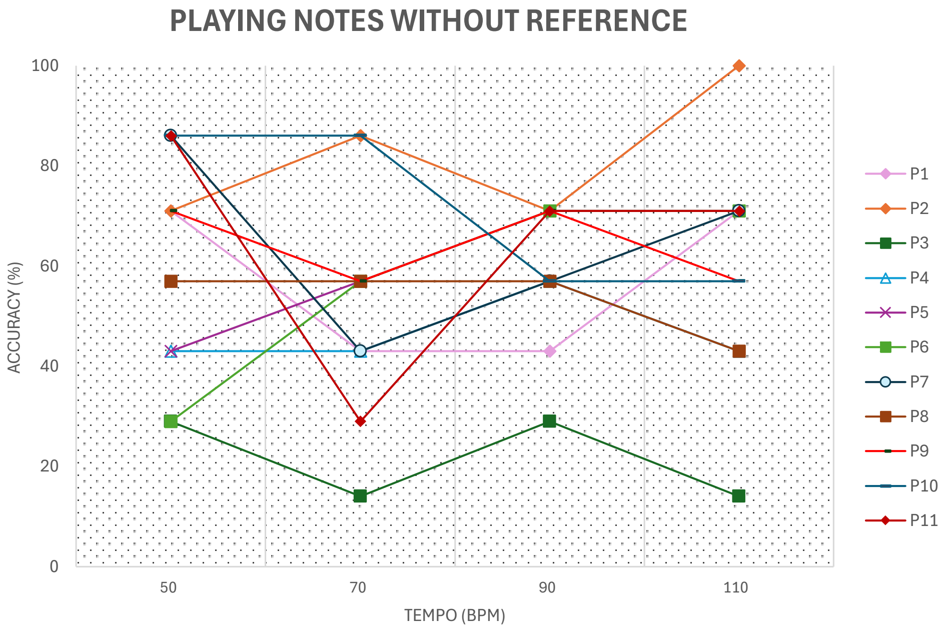


Fig. 30. Participant testing results: participants were asked to play the seven notes at four different rhythms with elbow placed in front of the guitar.

Next, the average time for adjusting the length mechanism was 1 minute and 23 seconds. For this, only one hand was allowed to be used, and the prosthesis was attached to the forearm. Finally, the participants were asked to answer the OPUS related questions. The modified questions from the OPUS questionnaire were used as follows:

1. The prosthesis fits well
2. The weight of the prosthesis is manageable
3. The prosthesis is comfortable during use
4. It is easy to put on the prosthesis
5. The prosthesis looks good
6. The prosthesis is durable
7. The clothes are free of wear and tear from the prosthesis
8. Skin is free of abrasion and irritation
9. The prosthesis is pain free to wear

Fig. 31 shows the answers of the eleven participants. The horizontal axis corresponds to the number of questions listed and the vertical axis with the number of participants that chose a certain response. In addition, Fig. 32 shows the answers to participants to the question “what type of improvement do you think the reference point is”. Regarding the OPUS questionnaire, the fitting, durability, weight and easy to put on questions were the strongest points. Having discomfort and skin irritation were the main negative points.

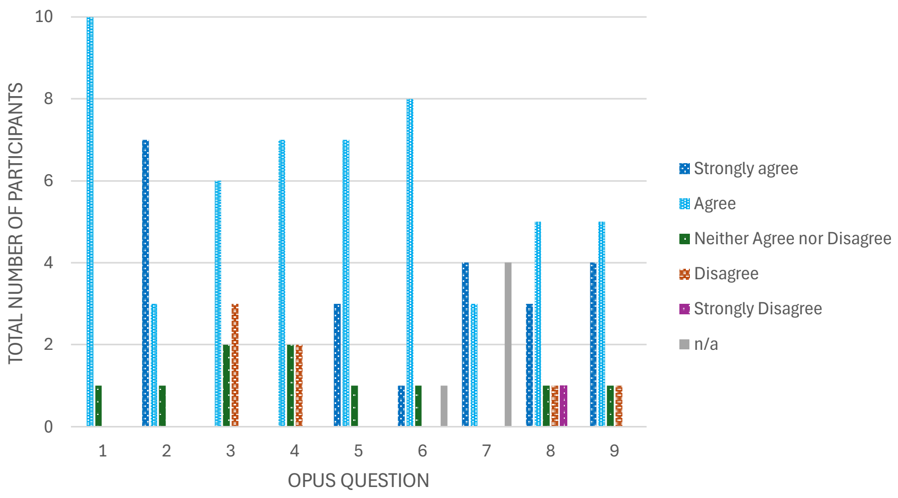


Fig. 31. Participant testing results: responses to modified OPUS questionnaire

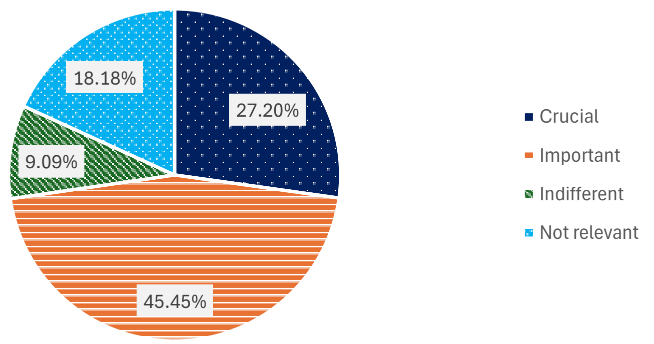


Fig. 32. Participant testing results: Answers to the question what type of improvement the reference point is

Feedback from participants regarding the device and how they felt was received. The strongest points as feedback from the participants were related to the prosthesis being lightweight, the angle mechanism and parameter changing advantages. The design and appearance of the model appeared also as positive inputs. Areas of opportunities were detected regarding the device stability and additional degrees of freedoms to have even more combinations.

4.3 Interpretation of results

4.3.1 Parameter measurements interpretation

The parameter measurements show that the device performs as intended and can resist the expected force when playing guitar. Requirements 1 to 4 were achieved based on the measurements obtained. This leads to better device performance. Requirements 5, 8 and 9 were also achieved since the model was designed along the desired constraints and was able to withstand successfully the expected loads while playing acoustic guitar.

Referring to the assembly durations, it was seen the first assembly took more than 15 minutes, whereas the last one took slightly more than seven minutes. This invites to think that the very first time to assemble the device is more difficult because of the user trying out different strategies of assembling the device. This includes the order of assembly. However, with time, the assembly process was reduced by half. The phase that took more time was the last one. This could be due to the difficulty of assembling small parts involved in the ball and socket system and the plectrum gripper. It would be beneficial to conduct these time measurements with users with upper limb differences, in order to compare strategies and support points that can be used. Based on this, optimization in the design could take place with focus on reducing time for the first assembly. Once the user achieves this, only the Velcro straps must be loosened, as well as the plectrum if a new one will be used (in addition to the parameter adjusting before playing).

4.3.2 User functionality test interpretation

Requirements 6,7 and 10 have been accomplished since the tasks were completed. Don/doff by the user with one hand could be improved. The results graphs show that playing with the elbow placed above the guitar was translated in greater accuracy for tempos 50, 70 and 90 BPM. Having no reference appeared to be slightly better in accuracy at 110 BPM than having the reference. These last results can happen since Task 4 at 110 BPM was the very last task that participants needed to do. Since participants already had three other tasks to familiarize themselves with the device and the instrument, this can be a primary reason. It was expected that the tasks with visual feedback were going to be the preferred ones. Among the people that preferred Task 4 rather than Task 2 it was mainly due to time using the device. Participants that were familiarized with stringed instruments (P1, P3, P6 and P10) had better performances in average with the elbow above the guitar. P1 suggested better results in Task 4 due to the previous familiarization with that specific type of playing. All of them preferred to have the elbow as reference point. Even the other participants, part of their provided feedback was struggling without visual feedback. However, the elbow as reference point helped a lot. For Task 2, the best results were obtained at 70 and 90 BPM. This could be because playing too slow or too fast can distract the player from playing the right notes. Task 4 had the best results in 110 BPM, possibly due to previous tasks with the device. The worst tempo was 70 BPM (similar in Task 2). 100% accuracy was achieved by 50% of the experienced players and 28% of the inexperienced players. This represents that experienced players are more familiar with the elbow position. Participants suggested they were lost at some point without reference.

Regarding the modified OPUS questionnaire, the most answered response was that participants agreed with the question. The main negative points corresponded to skin irritation and discomfort. This occurred because the Velcro did not have cushioning material, which was uncomfortable for some participants. Positive points in terms of feedback from the participants included the model being lightweight, the working principle of the angle mechanism and the various possible adjustments for everyone. Design and appearance appeared also as positive input due to the device being printed in two colors. More degrees of freedom could be included to get closer to the strings. More than 70% of participants preferred elbow as reference point. This suggests the rest of participants tried out different postures to compensate for the lack of feedback.

5 Discussion

5.1 Results interpretation

Throughout the development and evaluation of the project, results indicate the fulfillment of the project's goal as well as the technical requirements and performance criteria: The device length, angle range of motion (ROM) and adaptability to various forearm widths were achieved in the desired ranges. The total model weight was found to be appropriate for this use. Different sizes of guitar plectrums were properly tried out with the device. The device was properly 3D printed using FDM and in the device functionality test, participants were able to play notes with various accuracy and speed values without visual feedback. Don/doff could be improved since some participants were struggling to find the ideal position of the device. Participants were able to use proper ROM for playing guitar. In terms of performance criteria, this device proves to be a cost-effective model that can be accessible to users lacking professional assistance. The mechanical properties of PLA allowed the model to be both lightweight and resist the force of guitar strumming. Even though assembly time was elevated at the beginning, after the third assembly the time was reduced by half. Adjustment while having the device attached to the forearm turned out to be challenging if only one hand is available. The design allows parts to be interchangeable not only for part replacement, but for new colors or aesthetic designs.

Adjustable parameters found in the commercially available products can also be achieved with this final model. This suggests that users without professional assistance would be able to download the parts and print them by themselves, i.e. it allows to have the same type of adjustments offered by companies and does not require fitting dimensions from a prosthetist. Another positive point is that no post-processing is needed for the parts besides removing the support material. The combination of length and angle adjustment allows users to try out different postures as well as trying out different stringed instruments such as the ukelele or the banjo. By having the elbow resting on top of the guitar, proper playing posture was obtained for participants.

Some trade-offs present in the study were the device being lightweight, but screws, nuts and straps were needed. This reduces the accessibility for users who do not have access to specific materials or tools. Another example is the device attachment to the forearm being practical but lacking stability while playing. In terms of sustainability, research proposes the possibility of having recycled PLA for diverse applications [49]. Even though the research group mentions further research is needed to comply with the desired mechanical properties, this appears to be an excellent solution for future applications that can make the device more sustainable. This is important, since the tendency of 3D printing (especially using FDM) is on the rise. Being able to make use of the recycled material would not only be useful for the environment, but also the cost of production.

5.2 Limitations

Although the project's goal was successfully completed, there are limitations to the project. First, the device functionality test included only one participant with upper limb difference. A greater number of the participants mentioned would portray a wider insight into the needs and requirements directly from the end users. Secondly, the time factor for the project's fulfillment was also an impediment to performing a greater number of interviews and feedback from users in different stages of the project. This is mainly due to the long waiting periods to receive an accepted ethics application. Finally, the concepts that were not selected as the final one were not worked in detail, possibly missing some interesting solutions that could have aided the project (e.g. a brace that would aid the system's stability).

5.3 Future recommendations

It is recommended to explore the optimization of the design in terms of removing the need for screws and nuts and reducing assembly time. This can increase accessibility to users who lack specific tools. Options for this proposal could be a mechanism for pressing the model and sliding until the users want. Friction forces and stress should be considered since this movement could make the device less durable with time. A second recommendation is to include counterweight for increased stability. This is mentioned because the current model relies on having Velcro straps maintaining the device firmly. Special attention should be given to not hindering the elbow placement above the guitar. Lastly, a longer user test involving users with upper limb differences would be very valuable for the project. This would mean letting the users use the device for a long period of time (e.g. 6 months) and assess whether with time and practice the user is able to improve the playing level and parameters such as sight reading can be improved.

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6 Conclusion

A passive adjustable 3D printed prosthesis for playing acoustic guitar is successfully designed and presented. The goal to design a device that helps users with upper limb differences was accomplished. This design is intended for people who do not have professional assistance for prosthetic development and wish to improve their guitar playing skills. The study involves design, development and evaluation techniques that are related to established technical requirements and performance criteria. The model is successfully 3D printed using Fused Deposition Modeling and PLA as material. The device was evaluated via parameters measurements and a device functionality test. Users with and without upper limb differences were involved in the evaluation phase of the design. Results show the device allows users to use their elbow as reference point, giving more assistance to improve speed, accuracy and the use of techniques such as strumming and fingerpicking without the need for visual feedback. The implementation of different adjustable mechanisms (length, angle, attachment and locking) allow the user to play with more freedom and better posture. This design gives an insight into the importance of 3D printing in the application of activity-specific prostheses and how parameters changing are crucial to let the users enhance their performance while doing a specific task. In conclusion, this device offers a solution to guitar playing users with upper limb differences with no opportunity to receive professional assistance in measuring, fitting or developing a tailored-made device. This design shows a viable direction for low-cost, activity-specific prosthetics and for improving the quality of life for the music-loving user.

Bibliography

[1] F. Cordella *et al.*, “Literature review on needs of upper limb prosthesis users,” *Frontiers in neuroscience*, vol. 10, p. 209, 2016, *doi: 10.3389/fnins.2016.00209*

[2] C. L. McDonald, S. Westcott-McCoy, M. R. Weaver, J. Haagsma, and D. Kartin, “Global prevalence of traumatic non-fatal limb amputation,” *Prosthetics and Orthotics International*, vol. 45, no. 2, p. 105, Apr. 2021, doi: 10.1177/0309364620972258.

[3] K. K. Chui, M. Jorge, S.-C. Yen, and M. M. Lusardi, *Orthotics and Prosthetics in Rehabilitation E-Book: Orthotics and Prosthetics in Rehabilitation E-Book*. Elsevier Health Sciences, 2019.

[4] M. Magbagbeola, “An AI Driven Approach to Autonomous Sensory Feedback for Upper Limb Prosthesis,” Doctoral, UCL (University College London), 2022. Accessed: Nov. 27, 2024. [Online]. Available: https://discovery.ucl.ac.uk/id/eprint/10152190/

[5] W. R. Frontera and J. K. Silver, *Essentials of Physical Medicine and Rehabilitation E-Book: Musculoskeletal Disorders, Pain, and Rehabilitation*. Elsevier Health Sciences, 2018.

[6] N. Pickard *et al.*, “Introducing an adjustable upper limb prosthesis into a Ugandan clinical service: impacts on free living behaviour and prosthetic use,” *Sci Rep*, vol. 15, no. 1, p. 11585, Apr. 2025, doi: 10.1038/s41598-025-96779-w.

[7] H. Mano, S. Fujiwara, and N. Haga, “Effect of prostheses on children with congenital upper limb deficiencies,” *Pediatrics International*, Apr. 2020, doi: https://doi.org/10.1111/ped.14265.

[8] M. A. Battraw, P. R. Young, W. M. Joiner, and J. S. Schofield, “A multiarticulate pediatric prosthetic hand for clinical and research applications,” *Front. Robot. AI*, vol. 9, Oct. 2022, doi: 10.3389/frobt.2022.1000159.

[9] L. Trent *et al.*, “A narrative review: current upper limb prosthetic options and design,” *Disability and Rehabilitation: Assistive Technology*, vol. 15, no. 6, pp. 604–613, Aug. 2020, doi: 10.1080/17483107.2019.1594403.

[10] B. Maat, G. Smit, D. Plettenburg, and P. Breedveld, “Passive prosthetic hands and tools: A literature review,” *Prosthet. Orthot. Int.*, vol. 42, no. 1, pp. 66–74, Feb. 2018, doi: 10.1177/0309364617691622.

[11] D. DaFonseca, H. Daley, and W. Hill, “Enhancing upper limb prosthetic fabrication with 3D printing technology: opportunities and applications,” in *Myoelectric Controls Symposium*, 2024. Accessed: Nov. 27, 2024. [Online]. Available: https://conferences.lib.unb.ca/index.php/mec/article/view/2494

[12] M. Hofmann, J. Harris, S. E. Hudson, and J. Mankoff, “Helping Hands: Requirements for a Prototyping Methodology for Upper-limb Prosthetics Users,” in *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, San Jose California USA: ACM, May 2016, pp. 1769–1780. doi: 10.1145/2858036.2858340.

[13] T. Sims, A. Cranny, C. Metcalf, P. Chappell, and M. Donovan-Hall, “ Participatory design of pediatric upper limb prostheses: qualitative methods and prototyping,” *Int J Technol Assess Health Care*, vol. 33, no. 6, pp. 629–637, Jan. 2017, doi: 10.1017/S0266462317000836.

[14] J. L. Kanas and M. Holowka, “Adaptive upper extremity prostheses for recreation and play,” *Journal of Pediatric Rehabilitation Medicine*, vol. 2, no. 3, pp. 181–187, 2009, doi: 10.3233/PRM-2009-0082.

[15] R. Raj, “Development of a Modular Activity-Specific Upper Limb Prosthesis,” *UNO Student Research and Creative Activity Fair*, Mar. 2021, [Online]. Available: https://digitalcommons.unomaha.edu/srcaf/2021/schedule/7

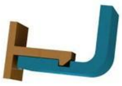
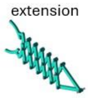
[16] F. A. C. Jr, “Prosthetic attachment,” US5062860A, Nov. 05, 1991 Accessed: Mar. 07, 2025. [Online]. Available: https://patents.google.com/patent/US5062860A/en?q=(upper+limb+prosthesis+for+musical+instruments)&oq=upper+limb+prosthesis+for+musical+instruments

[17] E. P. Gallagher, “Prosthetic guitar pick,” US3992975A, Nov. 23, 1976 Accessed: Mar. 07, 2025. [Online]. Available:

https://patents.google.com/patent/US3992975A/en?q=(PROSTHETIC+GUITAR+PICK+gallagher)&oq=PROSTHETIC+GUITAR+PICK+gallagher
[18] "TRS-Catalog-2023-08-22_web.pdf." TRS. https://www.trsprosthetics.com/wp-content/uploads/2022/09/TRS-Catalog-2023-08-22_web.pdf (accessed Mar. 11, 2025).
[19] De Hoogstraat Orthopedietechniek, "De Hoogstraat Orthopedietechniek," *Dehoogstraatorthopedietechniek.nl*, 2025. https://www.dehoogstraatorthopedietechniek.nl/ (accessed Mar. 11, 2025).
[20] "music | Koalaa," Koalaa. https://www.yourkoalaa.com/music (accessed Mar. 11, 2025).
[21] P.-H. Wu and J.-S. Shieh, "3D printed prosthetic hands," in *2016 International Conference On Communication Problem-Solving (ICCP)*, Sep. 2016, pp. 1–2. doi: 10.1109/ICCPS.2016.7751130.
[22] B. Romero-Ángeles *et al.*, "Design and Manufacture of a Forearm Prosthesis by Plastic 3D Impression for a Patient with Transradial Amputation Applied for Strum of a Guitar," in *Engineering Design Applications*, A. Öchsner and H. Altenbach, Eds., Cham: Springer International Publishing, 2019, pp. 97–121. doi: 10.1007/978-3-319-79005-3_8.
[23] J. Camilo, "Prototipo de prótesis de miembro superior para tocar guitarra," *Repositorio Institucional Séneca*, 2022. https://hdl.handle.net/1992/25476 (accessed Jun. 29, 2025).
[24] "e-NABLE Devices Catalog," e-NABLE. https://hub.e-nable.org/s/e-nable-devices/wiki/overview/list-categories (accessed Mar. 31, 2025).
[25] J. Silva, M. Silva, B. Soares, C. Quintão, A. R. Londral, and C. Quaresma, "Multi-activity 3D printed assistive technology in children: a case study," *Assistive Technology*, vol. 0, no. 0, pp. 1–6, Sep. 2023, doi: 10.1080/10400435.2024.2328091.
[26] M. Bogliolo, L. Turolla, F. Salvatore, J. Segre, E. Parodi, and M. Casadio, "Design and 3D Printing of Low-Cost Functional Sports Devices for the Upper Limb," *Prosthesis*, vol. 7, no. 1, p. 17, Feb. 2025, doi: https://doi.org/10.3390/prosthesis7010017.
[27] J. ten Kate, G. Smit, and P. Breedveld, "3D-printed upper limb prostheses: a review," *Disability and Rehabilitation: Assistive Technology*, vol. 12, no. 3, pp. 300–314, Apr. 2017, doi: 10.1080/17483107.2016.1253117.
[28] R. A. Inta, "The acoustics of the steel string guitar," Thesis, UNSW Sydney, 2007. doi: 10.26190/unsworks/17545.
[29] S. Carral and M. Paset, "The influence of plectrum thickness on the radiated sound of the guitar," *The Journal of the Acoustical Society of America*, vol. 123, no. 5, pp. 3380–3380, May 2008, doi: https://doi.org/10.1121/1.2934020.
[30] "Royal Conservatory Organization Review 2024 Web.pdf." Glenn Gould School. https://peqab.ca/Private/Royal%20Conservatory/Royal%20Conservatory%20Organization%20Review%202024%20Web.pdf (accessed Mar. 07, 2025).
[31] "étude." Cambridge Dictionary. https://dictionary.cambridge.org/dictionary/english/etude (accessed Mar. 07, 2025).
[32] M. A. Moore, "Learn to Play the Guitar: A Prosthetic's Viewpoint," University of Tennessee - Knoxville, May 2002. Available: https://trace.tennessee.edu/cgi/viewcontent.cgi?article=1579&context=utk_chanhonoproj
[33] C. Gamboa Zamorano, "Ergonomic determinants related musculoskeletal disorders and practice of classical guitar," Universidad El Bosque, 2016. Accessed: May 19, 2025. [Online]. Available: https://repositorio.unbosque.edu.co/server/api/core/bitstreams/a2488b56-48f8-4289-9aa2-34501d3afbd1/content
[34] X. Laverde, "Sight-reading and the Modern Guitar - Three Continents One Dream," thesis, Open Access Te Herenga Waka-Victoria University of Wellington, 2024. doi: 10.26686/wgtn.26878858.
[35] M. Sardelli, R. Z. Tashjian, and B. A. MacWilliams, "Functional Elbow Range of Motion for Contemporary Tasks," *JBJS*, vol. 93, no. 5, p. 471, Mar. 2011, doi: 10.2106/JBJS.I.01633.
[36] S. U. Islam, A. Glover, R. J. MacFarlane, N. Mehta, and M. Waseem, "The Anatomy and Biomechanics of the Elbow", doi: 10.2174/1874325002014010095.
[37] "Total Elbow Joint Replacement," Direct Orthopedic Care. https://www.directorthocare.com/total-elbow-joint-replacement/ (accessed May 21, 2025).

[38] P. Fitzgibbons and G. Medvedev, “Functional and Clinical Outcomes of Upper Extremity Amputation,” *Journal of the American Academy of Orthopaedic Surgeons*, vol. 23, no. 12, pp. 751–760, Dec. 2015, doi: 10.5435/JAAOS-D-14-00302.
[39] E. J. van Zuylen, A. van Velzen, and J. J. D. van der Gon, “A biomechanical model for flexion torques of human arm muscles as a function of elbow angle,” *Journal of Biomechanics*, vol. 21, no. 3, pp. 183–190, Jan. 1988, doi: 10.1016/0021-9290(88)90168-6.
[40] “Upper Arm & Elbow,” BODY SMART. https://bodysmart.healthcare/arm/ (accessed May 16, 2025).
[41] V. Boeijen, *Delft Design Guide (revised edition): design strategies and methods.* S.L.: Bis Publishers B V, 2020.
[42] M. J. Walker, E. Goddard, B. Stephens-Fripp, and G. Alici, “Towards Including End-Users in the Design of Prosthetic Hands: Ethical Analysis of a Survey of Australians with Upper-Limb Difference,” *Sci Eng Ethics*, vol. 26, no. 2, pp. 981–1007, Apr. 2020, doi: 10.1007/s11948-019-00168-2.
[43] “Continuous line drawing of young man playing guitar vector illustration | Premium Vector,” Freepik. https://www.freepik.com/premium-vector/continuous-line-drawing-young-man-playing-guitar-vector-illustration_35895240.htm (accessed Jun. 27, 2025).
[44] H. Yang *et al.*, “A lightweight prosthetic hand with 19-DOF dexterity and human-level functions,” *Nat Commun*, vol. 16, no. 1, p. 955, Jan. 2025, doi: 10.1038/s41467-025-56352-5.
[45] “How to calculate the cost of 3D printed parts.” HP. https://www.hp.com/us-en/printers/3d-printers/learning-center/calculate-3d-printed-parts-costs.html (accessed May 21, 2025).
[46] A. J. R. Barcena, P. Ravi, S. Kundu, and K. Tappa, “Emerging Biomedical and Clinical Applications of 3D-Printed Poly(Lactic Acid)-Based Devices and Delivery Systems,” *Bioengineering (Basel)*, vol. 11, no. 7, p. 705, Jul. 2024, doi: 10.3390/bioengineering11070705.
[47] “OPUS SATISFACTION (2014).pdf.” Rehabilitation Institute of Chicago. https://www.sralab.org/sites/default/files/2017-12/OPUS%20SATISFACTION%20%282014%29.pdf (accessed Jun. 28, 2025).
[48] L. Costalonga, “Biomechanical Modelling of Musical Performance: A Case Study of the Guitar,” Thesis, University of Plymouth, 2009. Available: https://pearl.plymouth.ac.uk/fose-theses-other/376/
[49] M. R. Hasan, I. J. Davies, A. Pramanik, M. John, and W. K. Biswas, “Potential of recycled PLA in 3D printing: A review,” *Sustainable Manufacturing and Service Economics*, vol. 3, p. 100020, Jan. 2024, doi: 10.1016/j.smse.2024.100020.

Appendix A: Morphological table

Attach to limb location	Lateral attachment(s)  [a]	Surrounding  [b]	Distal attachment  [c]	Top attachment  [d]	Beneath attachment  [e]			
Adapt to forearm	Screws  [f]	Cantilever snap-fit  [g]	Zip  [h]	Tying  [i]	Velcro straps  [j]			
Adjust length	Pivot point  [k]	Pin-and-hole  [l]	Rail with gear  [m]	Flexible extension  [n]	Press and move  [o]	Sliding  [p]	Scissor extension  [q]	Telescope  [r]
Adjust angle	Lockable ball and socket  [s]	Position change  [t]	Stepless adjustment  [u]	Rotating dock  [v]	Nut and bolt  [w]			
Adjust width	Circular rotation  [x]	Circular assemble  [y]	Horiz./vertical attachment  [z]					
Hold guitar pick	Bolts/screws  [aa]	Clamping  [bb]	Torsion spring  [cc]					

References

- A: https://www.istockphoto.com/nl/fotos/woman-forearm
- B: https://www.orfit.com/prosthetics-orthotics/blog/benefits-of-flexible-inner-sockets
- C: https://www.istockphoto.com/nl/fotos/woman-forearm
- D: https://www.istockphoto.com/nl/fotos/woman-forearm
- E: https://www.istockphoto.com/nl/fotos/woman-forearm
- F: https://www.amazon.nl/-/en/available-Machine-Screws-Phillips-Stainless/dp/B07FX6GCBZ
- G: https://nl.pinterest.com/pin/807903620640109476/
- H: https://www.amazon.com/YKK-Closed-Pockets-Golden-Variety/dp/B00ZLNQBOU
- I: https://www.shutterstock.com/es/image-photo/yellow-blue-ropes-tied-by-complicated-19136569
- J: https://www.securecableties.com/24-x-1-12-inch-heavy-duty-black-cinch-strap-5-pack
- K: https://www.huyett.com/blog/shoulder-bolts-an-introductory-guide
- L: https://www.amazon.ca/STEEL-Adjustable-Fitness-Rack-Pulley/dp/B0CNWP39WD
- M: https://www.alibaba.com/product-detail/Gear-Rack-Rail_1600396606832.html
- N: https://www.amazon.com/LASCO-03-4315-Flexible-Extendable-Extension/dp/B000FSSPZ4
- O: https://rodapin.com/en/professional-metallic-guide-cutter-18-mm/
- P: https://www.amazon.in/BUD-Industries-AS-5000-Sliding-Mechanism/dp/B005T57T8M
- Q: https://grabcad.com/library/scissor-extension-arm-1
- R: https://www.highpointscientific.com/apertura-2inch-50mm-long-extension-tube-ext50
- S: https://www.thorlabs.com/thorproduct.cfm?partnumber=MTRB3
- T: https://allmusic.com.co/products/apoya-pie-para-guitarra-08-gt
- U: https://ttap.co.uk/product/adjustable-portable-laptop-stand/
- V: https://www.networkhardwares.com/en-nl/products/compulocks-189bgrplck-compulocks-universal-tablet-grip-and-security-stand-black-189bgrplck
- W: https://diy.stackexchange.com/questions/138766/how-to-fasten-rotating-pieces-without-self-tightening-or-loosening
- X: https://www.daraz.com.np/products/360-degree-rotating-arm-wrist-strap-with-rotation-attachment-for-gopro-fusion-hero-i144584716.html
- Y: https://www.myminifactory.com/object/3d-print-hands-free-round-doorknob-arm-attachment-1-0-114932
- Z: https://grabcad.com/library/formula-student-front-wing-2-regulations-2018-1
- AA: https://frscott.co.uk/blog/set-screws-and-bolts-what-is-the-difference/
- BB: https://www.amazon.es/grande-resistente-viento-antideslizante-engrosada/dp/B0D8RLQQ6X
- CC: https://lesjoforssprings.com/insights/what-is-a-torsion-spring/

Appendix B: Device test raw data

Task 2 (elbow as reference + no visual feedback)	Tempo (BPM)	Accuracy (%)										
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
	50	86	86	43	57	43	86	29	57	43	71	86
	70	43	71	86	57	57	86	71	86	57	71	43
	90	43	71	100	43	43	100	100	71	71	71	43
	110	29	71	86	71	57	43	57	43	57	86	43

Task 4 (no reference + no visual feedback)	Tempo (BPM)	Accuracy (%)										
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
	50	71	71	29	43	43	29	86	57	71	86	86
	70	43	86	14	43	57	57	43	57	57	86	29
	90	43	71	29	57	71	71	57	57	71	57	71
	110	71	100	14	43	71	71	71	43	57	57	71