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Facilitating the Selection of a Myoelectric Prosthesis Using Virtual Reality for Upper Limb Amputee Patients

A Proof of Concept

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Abstract

Myoelectric upper limb prostheses aim to allow an amputee to accomplish everyday tasks again. Over the years, with the development of new technology, the number of prostheses available on the market has increased, so the choice of the most appropriate model is a difficult decision for an upper limb amputee (ULA) patient. Without the possibility of testing the different devices, it is really difficult for the patient to know which one is best adapted to their needs.
This study aims to develop a tool that facilitates this selection. The solution developed gives the patient an opportunity to be immersed in an environment, using Virtual Reality (VR), where different prostheses can be tested. The environment was built with Unity software. Thanks to two electrodes placed on their forearm, the subject can virtually control the prostheses. Three commercially available myoelectric prostheses were implemented in this prototype.
A qualitative pilot study was conducted to test the prototype. This experiment involved five healthy subjects. The purpose was to compare the participants' opinion of each myoelectric prosthesis before and after testing it virtually in our VR environment using a computer based questionnaire. From that experiment, it can be observed that the VR environment developed had an effect on the subjects' opinion of each prosthesis. While this is a promising proof of concept, our virtual tool will need further iteration and development, as well as a larger pool of participants and a wider experimental scope.

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We also would like to address a special thank to Grégoire's family for having the patience to test our prototype.
Last but not least, the work could not have been completed without the support of our friends and family.

Physiotherapy and Engineering : a Pluridisciplinary Collaboration

This thesis is the result of a close collaboration between one physiotherapy and two engineering students. Throughout the year, we have discovered the benefits of working together. Firstly, because the research topic required a knowledge of both disciplines. For instance, physiotherapy skills were necessary to understand the anatomy of the hand and to prepare for the clinical experience, whereas the engineers, thanks to their coding skills, focused on the implementation of the VR tool and prostheses.
Furthermore, during our respective university studies, we have learned completely different ways to approach a problem, one of the major asset of a pluridisciplinary collaboration. Exchanges between both parties enabled us to simplify - and synthesise - the language and the explanation to make it understandable for everybody.

List of Abbreviations

ADLs Activities of Daily Living

DIP Distal Interphalangeal

DoF Degree of Freedom

EMG Electromyography

GO Game Object

HMD Head-Mounted Display

MCP Metacarpophalangeal

Mvt Movement

PIP Proximal Interphalangeal

RoM Range of Motion

TM Trapezo-metacarpal

ULA Upper Limb Amputee

VR Virtual Reality

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Introduction

Worldwide the estimated number of upper limb amputee (ULA) patients amounts to three million people. However, among them, a small majority has the opportunity to have a prosthesis. It exists two types of prostheses: either an electrical **active** prosthesis, either a **passive** one. Despite of the great improvement during this last decades, the most popular category of prostheses is still today the passive ones, meaning prostheses that only have an aesthetic function [1].
After an amputation, the patient has to select the type of prostheses that best suits him/her. Many factors come then into play: obviously cost, whether the prosthesis is covered by the health insurance or not, aesthetics, complexity of use, the motivation and the age of the person.

The primary cause of upper limb amputation is trauma (up to 90%), meaning an amputation caused by a physical injury. The other causes are malignancy (the presence of a malignant tumour), vascular disease, congenital deformity and infection. The majority of the amputees are male (75%) [2]. The most common upper limb amputation is finger amputation, up to 90% [3][1]. Losing a limb has a huge impact on the daily life of the person. It affects his/her profession, especially for manual work, but also his/her autonomy in day-to-day life.

To address this issue, prosthetic technology has gone from simple hooks to advanced bionic prostheses. The term *bionics* comes from the combination of *bio* and *nics* as the end of the word electronics. It can be defined as *"The study of electronic systems which function in the manner of organic systems"* [4]. These bionic prostheses are mechanically or electrically powered. *Myoelectric* prostheses belong to the second type. Sensors are placed on the residual muscles to receive the electric signals emitted by the muscles.

Nowadays, because of the increasing number of commercially available myoelectric prostheses, it is becoming more and more difficult for the patients to identify the most suitable prosthesis. Indeed, according to a Belgian ULA patient : *"The choice of the prosthesis was one of the most difficult part of the rehabilitation process."*, the testimony is available in **Appendix A**. This is mainly because the patients do not precisely know their requirements. They do not have the opportunity to try each prosthesis. Therefore, they have to choose the device on the basis of theoretical descriptions, and this may lead, in the end, to a rejection of the prosthesis.

[1] The survey was conducted on 396 subjects in 2012 in New York.

This thesis proposes a solution to address this problem by building a virtual environment to test different prostheses. By executing some virtual tasks, the patient should be better able to understand the control of the different available prostheses. Practically, the aim of this work is to set the foundations for research by exploring two main directions: on one hand the feasibility of such a tool, and on the other hand the degree of usefulness of this tool to ease the patient's choice.

The first sections of this work address theoretical points about anatomy, kinematics, and amputation of the upper limb. This allows us to have a full understanding of the arm and of what an amputation implies.
Then, a state of the art about myoelectric prostheses is presented in the second chapter. It reviews how a bionic prosthesis works with concrete examples such as the Greifer, Bebionic, i-Limb prostheses. This leads us to briefly consider the future of the bionic prostheses. Afterwards, the use of the Virtual Reality in rehabilitation is described.
In Chapter 3, the prototype developed is explained. The steps from the muscle computer interface to the virtual reality implementation are described in details. Then, the pilot experiment is presented step by step, followed by the Chapter 5, where the results obtained are displayed. Finally, the last chapter discusses the results and tracks for future research are proposed.

Chapter 1

Clinical Consideration

To understand the core of this thesis, it is first important to comprehend the whole context surrounding upper limb amputation. This chapter provides to start a global anatomical and kinematic description of the upper limb. Then, the levels, stages and effects of an amputation are explained.

1.1 The upper-limb: anatomical and kinematic description

1.1.1 Anatomy and physiology

The upper limb is a quite complex limb. It is composed of 32 bones, 26 joints, 60 muscles, and many sensitive and motor nerves [5]. The upper limb can be divided in 3 distinct regions, the upper arm, the forearm, and the hand. For the purpose of this research, it is focused on the anatomy and physiology of the forearm.

From the anatomic point of view, every skeletal muscle in the body has the same general characteristics. The main one is that they are all composed of **muscle fibres**, each one surrounded by endomysium, which is a connective tissue. When a bundle of muscle fibres is formed, it is called a fasciculus, and this one is surrounded by perimysium, which corresponds to all the endomysium adding up together. The bundle of fasciculus forms the fleshy part of the muscle, whereas tendons are formed when endomysium joins up at both end of the muscle. Tendons are the part of the muscle connecting the muscles to the bones [6].

Another important characteristic to understand is muscle innervation, summarized from Malmivuo *et al.* [7]. Surely, central nervous system controls voluntary muscle activation. Details about the whole process are not covered in this thesis. Instead, it will be seen how nerves and muscles interact together. A muscle is innervated by a **motoneuron**, which sends numerous axonal branches to the muscle fibres. The amount of motoneurons activated depends on the required contraction force and speed. A **neuromuscular junction** is a synapse allowing connection between an axonal branch of motoneurons and a muscle fibre. This complex, composed of a motoneuron and the muscle fibres it innerves, is called a motor unit (**Figure 1.1**).

To contract a muscle, acetylcholine is released at the neuromuscular junction, leading to a depolarization, meaning a contraction of every muscle fibre. It starts from the neuromuscular junction and it goes in the direction of both tendons. This is called a motor unit action potential, which is the summation of all action potentials generated by each muscle fibre.

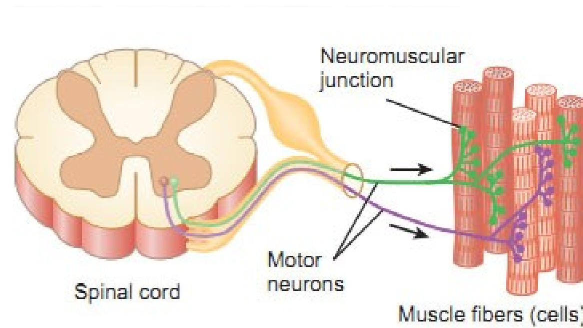


Figure 1.1: A motor unit consists of a somatic motor neuron plus all the muscles fibres it stimulates [8].

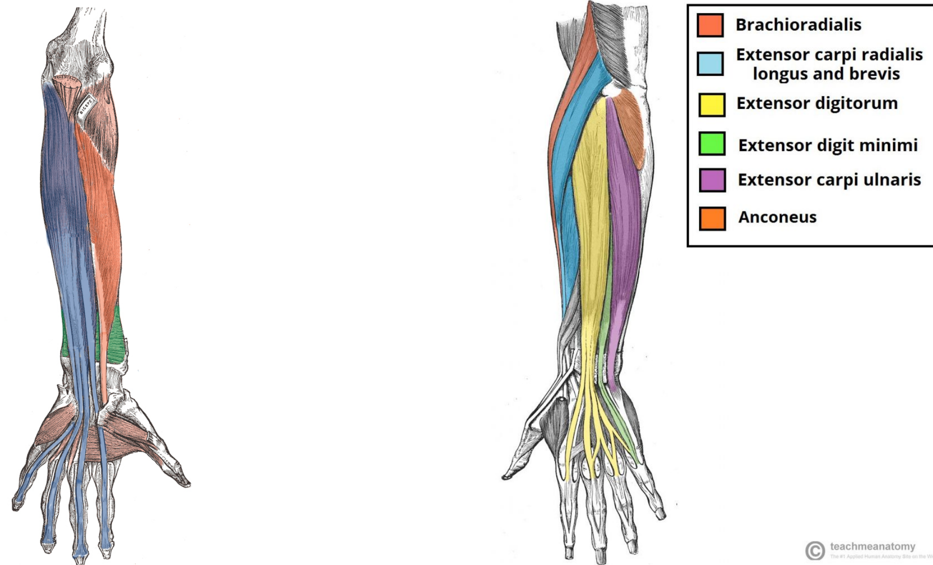
As explained earlier, a muscle allows movement of a bone and joint through tensioning of the muscle fibres. This tension is then transmitted to both ends of the muscle, towards each tendon. When the tension force surpasses the weight of the limb, a movement is initiated. The stronger the muscle contraction is, and thus the tendon tension, the faster the movement will be.

Wrist **flexion**, wrist ulnar deviation and fingers flexion are allowed by the flexor muscles of the forearm anterior compartment (**Figure 1.2a**). Wrist **extension** is allowed by the extensor muscles of the forearm posterior compartment, displayed in **Figure 1.2b**, except the brachioradialis and the extensor carpi radialis longus and brevis. Wrist radial deviation is allowed by the muscles of the forearm lateral compartment: the brachioradialis and extensor carpi radialis longus and brevis (**Figure 1.2b**). Finally, hand opening, meaning an extension of the fingers, is allowed by most muscles of the forearm posterior and lateral compartments. The different anatomical movements are displayed in **Appendix B**.

1.1.2 Kinematic analysis

In order to understand how a prosthesis tries to replicate real hand functionalities, it is necessary to understand hand kinematics. In this section, the study of the hand and wrist movements is developed. It includes a closer look at the **degrees of freedom** (DoFs) and **ranges of motion** (RoMs) of each joint.

The RoM of a joint is the aptitude to go through its complete spectrum of movements. There is a distinction to be made between passive and active RoMs. When an external force causes movement of the joint, it is called a passive RoM, typically



(a) Forearm anterior compartment.

(b) Forearm posterior and lateral compartments.

Figure 1.2: Each muscle group is represented by a different color [9].

if a therapist moves the limb of his/her patient. In the opposite, the active RoM is the range obtained by the patient moving itself. In general, the active RoM is associated with the maximal RoM [10].

The wrist joint, also called radiocarpal joint, is located at the distal end of the radial bone. This joint is an ellipsoid-type articulation. It has a biaxial DoF allowing flexion/extension as well as radial/ulnar deviation (movements described in **Appendix B**). Midcarpal joint is structured like the radiocarpal joint and increases the RoM of the wrist in both axes, **Figure 1.3**.

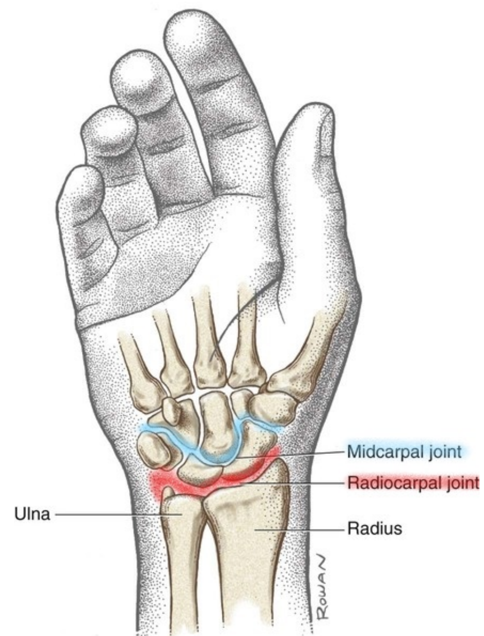


Figure 1.3: Micarpal and Radiocarpal joints of the wrist[11].

The RoM of the wrist is obtained by the summation of the ranges of those two articulations. In **Table 1.1**, the amplitudes for flexion and extension are displayed. Note that **ADLs** means activities of daily living, this notion will be developed further in **Section C.4**. It can be observed that the wrist has an amplitude going up to 45° for basic activities such as writing or grasping an object.

Mvt \Type of RoM	Active RoM	Passive RoM	RoM in ADLs
Flexion	80°	80°	45°
Extension	50°	80°	45°

Table 1.1: RoMs of the wrist joints (radiocarpal and midcarpal joints, 2 DoFs) [12].

Table 1.2 shows only the active RoMs for the ulnar and radial deviations. The contribution of each articulation, radiocarpal and midcarpal, is displayed for those two movements. The difference between radial and ulnar deviation is caused by the scaphoid bone and the radial styloid process, which are limiting the movement.

Mvt \Joint	Radiocarpal	Midcarpal	Total
Ulnar deviation	15°	25°	40°
Radial deviation	5°	10°	15°

Table 1.2: Active RoMs of the wrist joints for ulnar and radial deviation. Contributions of the radiocarpal and midcarpal joints are detailed [12].

Finger joints are more complex. By establishing a kinematic model of the hand, it can be observed that there are 4 degrees of freedom (DoFs) per finger and 5 DoFs for the thumb. Indeed as can be seen in **Figure 1.4**, each finger is composed of two interphalangeal `IP` joints: the distal `DIP` and the proximal `PIP`. These joints allow each flexion/extension (2 DoFs). Then there is the metacarpophalangeal `MCP` joint inducing flexion/extension and abduction/adduction (1 DoF for each thus 2 DoFs in total). The thumb has only one `IP` joint and one `MCP` joint. But in addition, there is the trapezio-metacarpal `TM` joint allowing flexion/extension and abduction/adduction (2 DoFs) [13].
The thumb `TM` joint has a very particular structure, it is also called saddle-shaped joint. This shape allows the thumb to perform a movement called *opposition*, which refers to the ability of the thumb to touch the other fingerprints. Fingers RoMs are detailed below on **Table 1.3**.

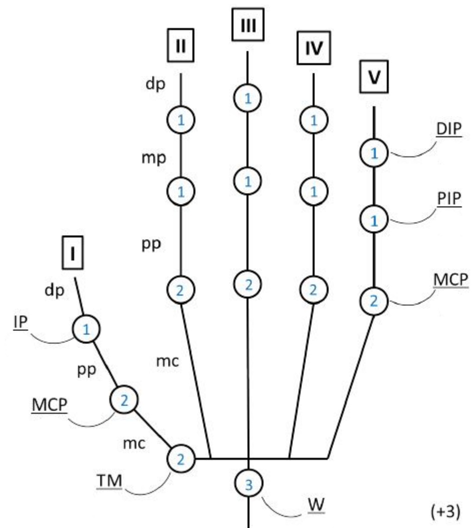


Figure 1.4: Palmar view of the right hand - 27 DoFs [14]. Fingers are numbered from I to V. The circled numbers represent the number of DoFs of each joint. The bones of the hand are indicated with the following abbreviations: dp= distal phalange, mp= middle phalange, pp= proximal phalange, mc= metacarpus.

Mvt \Joint	Thumb TM	Thumb MCP	Thumb IP	Finger MCP	Finger DIP	Finger PIP
Flexion	50°	50°-75°	70°-80°	90°	80°	120°
Extension	50°	<10°	10°-30°	30°-70°	5°-20°	0°
Abduction	60°	very small	/	30°-40°	/	/
Adduction	60°	very small	/	30°-40°	/	/

Table 1.3: Ranges of motion of the fingers [12].

1.1.3 Synergy and hand gesture

To understand the complexity of the hand gesture, the number of DoFs of the hand can be computed. The wrist has 3 DoFs: flexion/extension, supination/pronation, and finally, ulnar/radial deviation. In addition, there are 16 DoFs for the 4 fingers and 5 DoFs for the thumb. Leading to a total of **24 DoFs** for the hand module. Considering that the translation of the wrist can add 3 DoFs (indicated by a (+3) in **Figure 1.4**), because the hand can move in all the planes of a **3D space**. Indeed thanks to the arm, the hand can go up/down, side to side and forward/backward. It can be concluded that there are **27 DoFs**.
However, the model displayed in **Figure 1.4** is simplified and does not take into account all the muscles and tendons in the hand. To be really precise, one should consider the 36 muscles related to the thumb and the fingers, but also the tendons located in the hand, which would lead to a total of more than 60 DoFs [13].

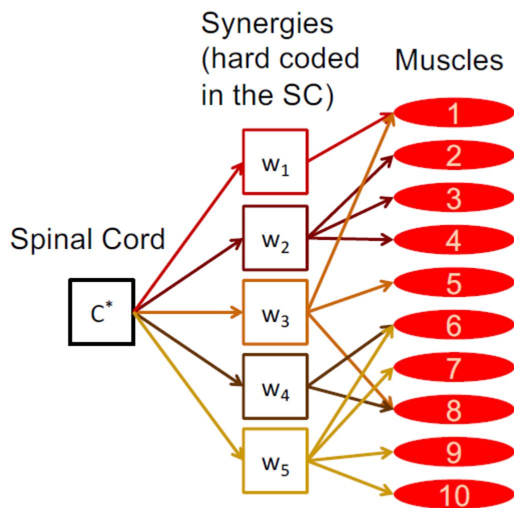


Figure 1.5: Synergy diagram [15]. Signals coming from the Spinal Cord (SC) are sent to the muscles in the form of synergies (w_i), these spinal modules activate each a specific muscle group.

This complexity demonstrates that the brain does not likely activate each muscle and tendon for a given movement, instead it executes a pattern. This is called the **muscle synergy** (**Figure 1.5**): a group of small muscles are recruited simultaneously to produce a given movement [16].
The motor signals that cause the movements go from the brain to the muscles through the **spinal cord**. The brain activates a **spinal module**, named w_i in the given Figure, in the spinal cord containing the activation pattern. Then, the activation signal is sent to the corresponding muscles. To sum up, the theory of synergy is proposed to explain how the brain simplifies the control of hand postures by reducing the control dimension.

Some movements are more complex and recruit more muscles than others. Hand gestures can be divided into two categories. The first one is called **global prehen-**

sion. It is the skill of the thumb to oppose the other fingers. Most of the movements executed by the hand consist of grasping tasks. There are different types of grasping, but in general it defines the action to hold an object with the hand. The second category takes into account the **finer movements**. They are more precise, require the ability to independently move each finger, like typing on a keyboard or playing the piano. So many of the patterns implemented in the prosthesis include the global prehension because they are the most useful.

1.2 Amputation

Currently, there are no precise statistics about ULA patients around the globe. Data is very difficult to obtain on a large scale. Nevertheless, in the United-States of America, the amputee population was estimated at two million persons in 2020, including almost a third of ULA patients [17].
In Belgium, in February 2020, an article was published by *Partenamut* [18] estimating the number of amputees at 7700. This number includes upper and lower limb amputations. Nevertheless, it must be emphasised that the number of lower limb amputee patients is much higher than the number of ULA patients. Indeed, if the same proportion than the one found in the USA is used, namely 2/3 for lower and 1/3 for upper limb amputations, the number of ULA patients in Belgium amounts to approximately 2500. As mentioned in the introduction, among the upper limb amputation nearly 90% of them have an amputated finger [3]. It leads to a total of approximately 250 patients that have a major amputation of the upper limb. Although this number is a rough approximation, it gives us a picture of the few cases identified.

1.2.1 Amputation levels

After amputation, the remaining part of the limb is medically referred to as the **residual limb**. In **Figure 1.6**, the different amputation levels are shown. Disarticulation consists in dislocating a joint, keeping the bones intact. Transhumeral refers to the amputation of the humerus bone while the **transradial** refers to the amputation of the radius and ulna bones (these two bones can be visualised in **Figure 1.3**).

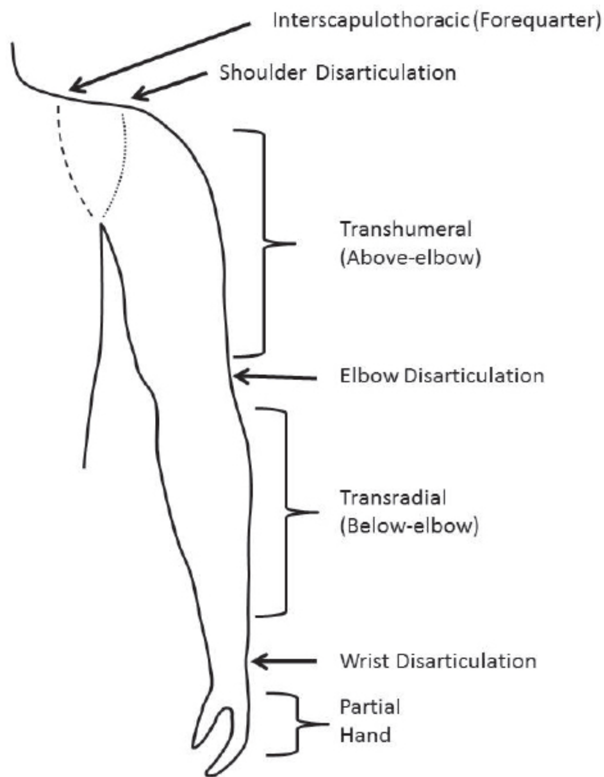


Figure 1.6: Levels of upper limb amputation [19].

This paper will be focused only on transradial amputation. To classify the different levels of a transradial amputation depending on the remaining length, the following terms are used: very short, short, medium and long. To maximize the range of motion, the length of the residual limb is essential. The movements of flexion and extension are directly related to the length of the forearm. The forearm can be divided in three parts: the distal third (hand side), the middle third and the proximal third (elbow side).

If the amputation occurs in the distal third, the patient can still manage the movements of pronation and supination. However, an amputation in the proximal third limits the movements to flexion and extension only. When a very proximal amputation is the only option, it is important to ensure the conservation of the bicipital tuberosity, which is a rugged surface on the radial bone where there is the distal insertion of biceps brachii. This is responsible for the active flexion of the elbow. To ensure a good fit for the prosthesis, at least 4cm of the ulna is required [20].

1.2.2 Amputation stages

The main phases of amputee rehabilitation are illustrated in **Figure 1.7**. It is important to know that the time needed for each step varies greatly from one patient to another [21].

- **Pre-operative stage** - in case where the surgery is scheduled, meaning not due to a trauma, the patient is prepared psychologically as much as possible and receives some explanations from the surgeon. During this period, the prosthetist can also meet the patient to explain the different options available depending on the resulting limb length.

- **Amputation Surgery and Post-operative stage** - the removal and closure of the limb are made. The length of stay in hospital varies from one patient to

another, ranging from 3 to 10 days. The care team is already active during this period to start rehabilitation. Their goal is to maintain the range of motion of the residual limb, to promote wound healing and to support the patient mentally. An important part of the post-operative stage is pain control. Over time, the pain should decrease steadily.

- **Pre-prosthetic training** - the residual limb is prepared to receive a prosthesis. As the stump still tends to swell during this phase, the patient wears a shrinker or a compression sock.

- **Prosthetic prescription and training** - at this stage the wound is completely healed. The prosthetist identifies the prosthesis that will best suit the patient, by asking questions about his/her lifestyle. Once the patient gets a prosthesis, he/she can start training. A example of a training program for prostheses developed by Ottobock can be found in **Appendix C**.

Figure 1.7: Amputation stages.

1.2.3 Effects of amputation

In this section, the most common effects of amputation are explained. It has to be noted that these vary greatly between patients. Many factors come into play including his/her age, health before the injury, psychological state, etc. Nevertheless, a non-exhaustive list of the consequences follows.

Phantom-limb pain

Phantom-limb pain affects up to 80 % of amputees. The pain takes various forms, and differs from case to case. It can be either temporary or chronic. The sensation can be described as a stabbing, achy or burning pain near the area of the missing limb. Each body part has its tactile representation in the brain in the form of a map. When a limb is missing, the brain does not receive a feedback from the severed neural cords anymore. The most common explanation of phantom limb pain is that this lack of input is misinterpreted by the brain and causes discomfort [22].

Nowadays, most of the treatments proposed are not wholly effective. Therapies can be pharmacological or mechanical. Some medication, such as ketamine and opioids, proved helpful in pain relief.

A concrete example of a mechanism-based treatment is mirror therapy. The basic idea is that a mirror is placed between the intact arm and the injured limb. While the patient is looking at the mirror image of the healthy arm, he/she has to execute some movements (**Figure 1.8**). The brain perceives the image of an intact limb instead of the phantom limb. This technique tricks the brain and releases the pain [23].

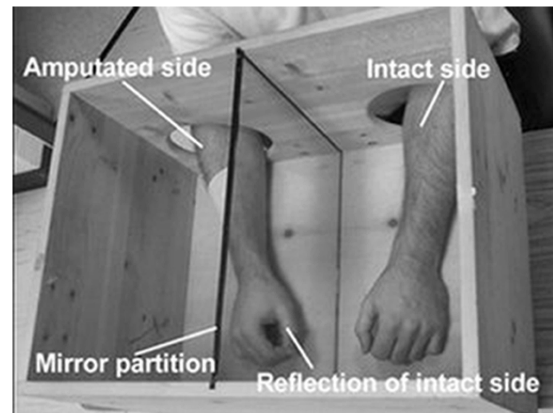


Figure 1.8: Illustration of the mirror box technique [24].

However, mirror therapy does have some limitations due to the constraints of being sat with the hands in a box containing the mirror. The illusion created can easily be broken. This is why recent studies have proposed the use of Virtual Reality. The patient is equipped with VR goggles and one glove. The residual limb is stimulated by small electrical impulses which allow the patient to receive a tactile feedback. Through virtual games, the patient has to execute tasks that require symmetrical movement of both hands [22].

Contracture of a joint

During the week following surgery, the residual limb stays in a static flexed position which can lead to contractures of the joint closest to the amputation site. As the joint is no longer stimulated by the pull of the muscles and tendons of the limb, the joint in question tends to pull up or inwards.

To prevent this, exercise sessions have to start by day 5 or 7, once the pain has eased. Throughout this phase, the aim is to steadily increase the range of motion of the residual limb. It is also essential that the patient moves the joint regularly throughout the day, as it would be activated during a normal day.

Contractures are often observed after a lower-limb amputation but can also occur after an upper-limb amputation. More specifically, it occurs easily around the elbow flexion region in the case of short transradial amputation [25].

Stump pain and infection

After surgery, some complications, such as infection, can occur . If the wound does not heal correctly, this may cause the wound to re-open again and become infected. To prevent these problems, the environment has to be kept clean and sterile. However, sometimes the patient also has problems with blood circulation which impedes healing. If the situation does not improve, at a certain point the only solution is to remove more of the residual limb or even the rest of the remaining limb.

In a better scenario, infections can only delay the placement of the prosthesis [26].

A distinction has to be made between stump pain and phantom-limb pain. The stump pain occurs in the residual limb and the phantom-limb pain, as explained above, arises from the missing limb. But it is observed that often both of these pains come at the same time, and more than 50% of cases, the patients experiencing phantom pain are also affected by stump pain. The main causes of stump pain are infections, problems in the bone or in the soft tissue, poor blood supply and circulation, a tumour or/and problems with the fit of the prosthesis [27].

Overuse syndrome

Another effect, often dismissed, is overuse of the remaining limb. The limb is subject to intensive use and repetitive stress, because it compensates for the missing limb. It can cause serious injuries, such as tendonitis. These inflammations require rest, time and warm or cold compresses to relieve the pain. Therefore, it is paramount that amputees are aware of this risk and are able to detect an overuse in its early stages [28].

Emotional effects

A major effect is the physiological consequences of the loss of a limb. Since trauma is the first cause of upper-limb amputation, the patient can suffer, amongst others, from post-traumatic stress disorder. Moreover, the person was not prepared to lose a limb, and so an adaptation period is needed. It affects not only body image but also social life. For some people, their social life is mainly built around physical activities. Consequently, they need to reorganize their way of living. Depression is often observed in patients. That is why psychological support is important both in the early stages and in the following steps [26].

Chapter 2

State of the art: Myoelectric Prostheses

The first part of this chapter shortly introduces the different categories of upper limb prostheses. The second part compares several commercially available prostheses. Then, the mechanism of 3 prostheses is explained in more details. These are the 3 prostheses that will be further implemented, for this thesis, in the virtual environment. Afterwards, the future generation of prostheses, which are more intuitiveness, is presented. Lastly, a brief section introduces the applications available using the virtual reality for ULA patients.

2.1 Categories of prostheses

Whereas this thesis is focused on the myoelectric prostheses, it is important to have a global view of the other categories of prostheses. According to Arm Dynamics©, there are five categories for the upper limb [29]:

- **Passive prosthesis** - the main purpose of these kinds of prostheses is the aesthetic. Nevertheless, it lends stability. These types are the lightest because no motors or mechanical devices are needed.
- **Body-powered prosthesis** - operated by cables and harness. Some people who do manual work will prefer this kind of prosthesis as they are relatively easy to use and provide a kind of feedback by pressing back the activation limb.
- **Electrically powered prosthesis / Bionic prosthesis** - using batteries and electrical motors. The remaining muscles are used to provide the input electrical signals via sensors placed on the arm.
- **Hybrid prosthesis** - combination between body-powered and electrically powered prosthesis. This category is often used for people with a high level of amputation such as the trans-humeral one.

- **Activity-specific prosthesis** - the aim is to meet a specific need, such as sport, for example. It can be applied for all types of prostheses: passive, body-powered or electrically powered.

2.2 Myoelectric prostheses overview

In this section, a review of some existing prostheses is made. **Table 2.1** summarises the features of 6 different bionic prostheses. Five of these prostheses are commercially available including four manufactured by Ottobock, which is a world leader in this field.

In the following table, the devices are evaluated according to 5 criteria: independence of fingers, passive movements available in the prosthesis, and number of actuators, grip patterns and electrodes.
The independence of fingers is an important feature, as it gives direct information about the dexterity and the degrees of freedom (DoFs) of the prosthesis.
A passive movement, which is the second criteria, expresses the capability of the users to move the wrist/thumb themselves with the other sound hand. It does not mean that they are not motorized, actually it can be both. The patients can either move the wrist passively or rotate the wrist thanks to a myoelectric activation.
Another characteristic covered is the number of grip patterns available. A grip pattern, as explained before, is the combination of the individual finger positions. In other words, it is the different positions of the hand implemented in the prosthesis.
The last criteria is the number of electrodes. For most conventional prostheses, 1 or 2 electrodes are used. This depends mainly on the condition of the residual muscles, whether they are exploitable or not.

Name	Independent fingers	Passive movements	Actuators	Grip patterns	Electrodes	Note
Greifer (Ottobock)	1	wrist	2	1	1-2	Functional
AxonHook (Ottobock)	1	wrist	2	1	1-2	Robust and simple
Michelangelo (Ottobock)	3	wrist	3	7	1-2	
Bebionic (Ottobock)	4	wrist-thumb	5	14	2	Proportional speed control
i-Limb Quantum (Ossür)	5	wrist-thumb	6	24	1-2	Proportional speed control
Adam's Hand (BionIT Labs)	5	(?)	1 (+2)	(?)	8	Light and intuitive

Table 2.1: Comparison of different existing hand prostheses. Unknown information is marked by *(?)*. [30, 31, 32, 33].

The two first devices presented, **Greifer** (**Figure 2.3**) and **AxonHook** (**Figure 2.1**), are the most simple and are comprised of a clamp. They are known to be functional and robust. Only one grip pattern is available, the possibility to close or to open the clamp in order to grasp an object. The Axon Hook and the Greifer both have 2 actuators in total because the wrist can be motorized [32]. This is optional, the users has to choose at the outset whether they want the motorized wrist option.

Figure 2.1: AxonHook, Ottobock [34].

Figure 2.2: Michelangelo, Ottobock [34].

The four following prostheses have a hand shape appearance. The **Michelangelo** hand (**Figure 2.2**) is unusual in that is has only 3 independent digits; thumb, index and middle fingers, while the ring and little finger passively follow the others. The first actuator of the Michelangelo allows the adduction/abduction movements of the thumb. The second one actuates the three active fingers.

One major difference between **Bebionic** (**Figure 2.4**) and **i-Limb Quantum** (**Figure 2.7**) is that the Bebionic thumb is not motorized [33], which explains why i-Limb has one extra actuator. The Bebionic needs 5 actuators, 4 for the main fingers and one for the wrist (which is optional). Note that having 14 patterns available, like the Bebionic, does not mean that the user can have them all at the same time. In fact, the user can switch between 8 patterns pre-selected [30].

Adam's Hand has only one DC motor and two servomotors which makes for a much lighter prosthesis compared to i-Limb Quantum and Bebionic for instance. The Adam's Hand prosthesis is described in details in **Appendix E**. Unlike the 5 other prostheses presented above, it is not yet commercialised. It belongs to the new generation of intuitive prostheses, a concept explained in **Section 2.3**. In this configuration, 8 electrodes are used [31].
Note that even after research, some information, such as the number of passive movements and grip patterns, is not easy to find, so question marks remain about this.

As the aim of this thesis is to facilitate the selection of a prosthesis for a patient by using Virtual Reality, the follow-up of this section is focused on the three prostheses that are implemented in our VR prototype: Greifer, Bebionic and i-Limb Quantum.

2.2.1 Greifer (Ottobock)

With this prosthesis, Ottobock proposes a solution for manual work: a simple clamp intended to provide fast and strong grip (**Figure 2.3**). A torch is embedded in order to light inside a toolbox for example. The grip force is adapted according by the muscle signal. The speed is adjustable with a range going from 8 to 180 mm/s. Wrist rotation is possible, either passively or electrically. Flexion and extension, with a range of 45°, is passively adjustable [35].
The cylinder, which is the pivot of the clamp, rotates when the clamp is opening/closing and it can also be used in a passive way in order to manually control movement.

Figure 2.3: Greifer Hook, Ottobock [35].

To catch signals from the muscles of the remaining forearm in the case of a transradial amputation, two electrodes are placed in direct contact with flexors and extensors of the forearm. One electrode controls the opening and the other one the closing. These electrodes are fixed inside the socket forearm, and the location is specific to each patient in order to provide the best EMG signals.

The user can easily replace the Greifer with a myoelectric hand such as the Bebionic. The bases of the 2 prostheses are compatible with the same forearm socket. It is not tricky for the user to switch from one to the other because the control uses the same approach.

2.2.2 Bebionic (Ottobock)

The first version of the Bebionic Hand came out in 2010, and was later bought out by Ottobock in 2017. This prosthesis is said to be precise in performing daily living activities. The thumb can only be moved manually and the four other fingers are motorized independently which gives a great dexterity of movement. The user can control up to 8 different grip patterns, selectable among the 14 available. As the Greifer, the movements are activated thanks to two electrodes placed on the remaining limb.

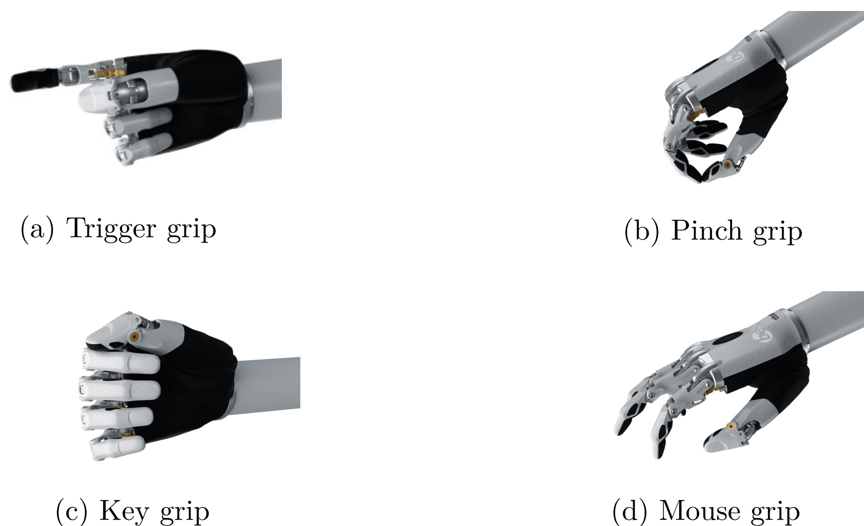
Figure 2.4: Bebionic Hand, Ottobock [36].

Proportional speed control is implemented in order to perform delicate tasks. In other words, the speed of movement is proportional to the intensity of the EMG

signals. To grasp a fragile object, such as a plastic cup, the user emits progressively low myoelectric signals in order to know exactly when to stop the closing movement.

Grip pattern selection

In **Figure 2.5** are displayed 4 of the 14 patterns proposed by Ottobock. The first one (**Figure 2.5a**) typically allows the use of spray bottles and power tools. The index finger remains straight in order to be able to press buttons. The other fingers stay against the palm to hold the object. In **Figure 2.5b**, the pinch grip permits the grip of small objects between first finger and opposing thumb. The key grip is really useful for daily tasks like cooking (**Figure 2.5c**). The four fingers are flexed to hold thin objects. The thumb is in an unopposed position and is pressed against the first digit. The last one, in **Figure 2.5d**, as indicated by its name, is suited to holding a computer mouse [37].



(a) Trigger grip (b) Pinch grip

(c) Key grip (d) Mouse grip

Figure 2.5: Bebionic: grip patterns [36].

Switching between the eight different grips

The thumb can be moved manually and has two positions as seen in **Figure 2.6**: opposition and lateral. The grips are classified as **primary** if they are used often in daily life, and as **secondary** if they are more specific. To switch from primary to secondary grips, the program switch has to be pushed for less than 2 seconds. This is located on the top centre of the hand. This button has several functions, including switching the prosthesis off and on by holding it for 3 seconds. Two grips are implemented in each grip group. For passing from one to another, for instance from Grip 1 to Grip 2, the muscle signals “Open + Open” or “Co-contraction” are used. The simple signals "Open" and "Close", each assigned to one electrode, are retained to activate the grip pattern itself. This way, 8 grip patterns are available at the same time.

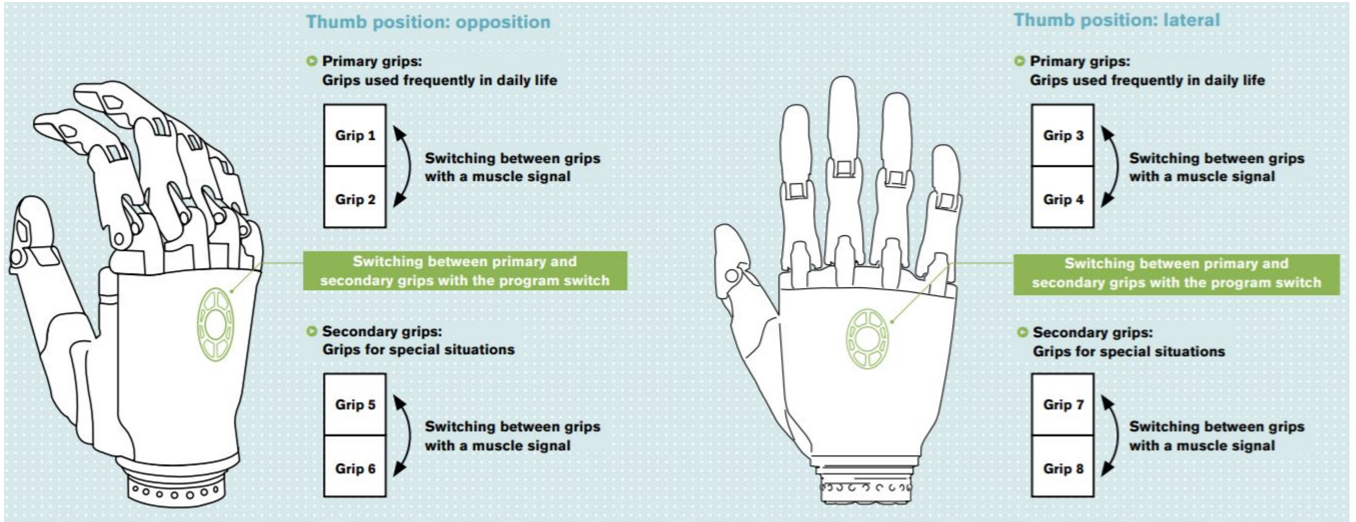


Figure 2.6: Switching options [30].

2.2.3 i-Limb Quantum (Össur, Touch Bionic)

Founded in 2000, Touch Bionic is specialised in upper limb prostheses. In 2016, Touch Bionics was acquired by Össur, a recognised company in the development of non-invasive prostheses. By the end of 2015, they claim they had equipped more than 5000 patients with their hand prostheses [38]. The most developed hand and wrist prosthesis is i-Limb Quantum (2015) illustrated in **Figure 2.7**.

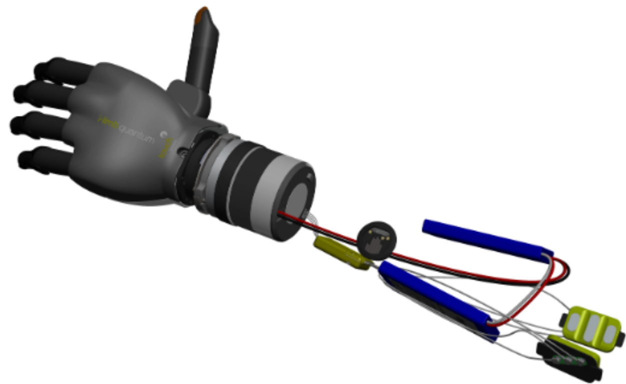


Figure 2.7: i-Limb Quantum + rotating wrist and electrodes [39].

There are different ways to control the prosthesis in order to make it accessible and adaptable to each patient. In total, there are 24 pre-programmed patterns + 12 customized patterns. Each pattern corresponds to a specific hand posture, with the 5 digit movements (1 actuator per digit) and potentially a wrist rotation (for specific tasks as illustrated in **Figure 2.8**). Two EMG signals are responsible for the activation of the selected pattern: open - close. This requires precise placement of the electrodes [39].

Grip pattern selection

The selection of the grip pattern is possible via several means [40]:

- **Application** (patented): requires an Apple iPhone. The app permits selection

of the grasp pattern. Also, the app is used to adapt the prosthesis to the patient for things such as the signal threshold. Indeed, the voltage of the myoelectric signals emitted may vary from one user to another.

- **Gesture control** (patented): to enter in this gesture control, the users have to trigger the jump of the index by maintaining a long opening signal. Then, they have to move the prosthesis in one of the 4 directions (up, down, left, right). One hand position is assigned to each direction. Once the move is done, the new grip pattern is selected.
- **Proximity chip** (patented): passing in front of a small chip causes the grasping mode to change. For instance, when the users are typing on the keyboard and they need to change their grip pattern to grasp the mouse, the chip placed on the desk can be used to activate the change.
- **Muscle signal**: a quick double/triple muscle contraction or co-contraction while the hand is already open permits the user to change the grasp mode.

Grip activation control

The grip itself is controlled by different ways:

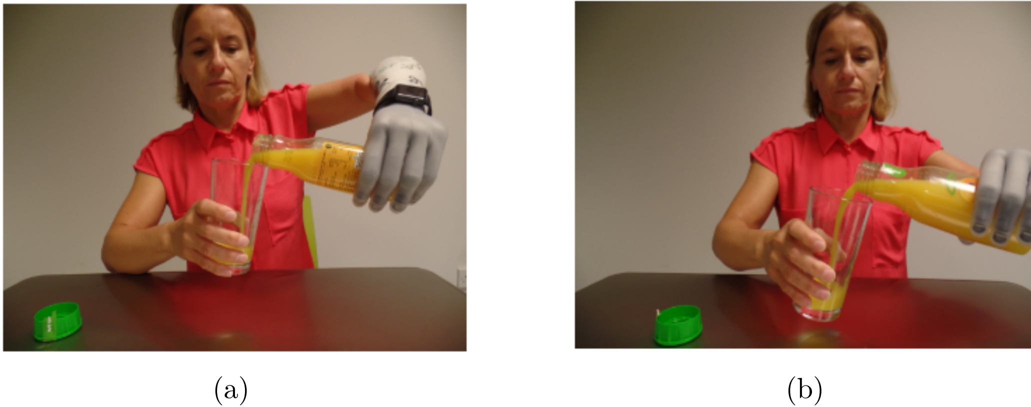
- **Auto-grasp**: sensors able to detect the object sliding and, where appropriate, adapt the grasping force.
- **Velocity control**: the finger's velocity is proportional to the amplitude of the EMG-signal.
- **Vari-grip option**: the grip force is proportional to the duration of the close-command.

Wrist control

Wrist rotation is essential for some movements. In **Figure 2.8a**, it can be observed that the lady is not in a comfortable position to fill her glass, the wrist has not rotated in this instance. Whereas in **Figure 2.8b**, by adapting the angle of the wrist, the movement is much more natural.
In total, the wrist of the i-Limb Quantum can achieve 4 positions: open, close, supination and pronation. Several methods allow its control [40]:

- **Automatic:** wrist rotation is imposed by the grasp pattern.
- **Intelligent:** if a second set of muscles is available, after recording several patterns, control is possible.
- **Up/Down:** the control is done via the same electrodes as the hand. But a quick command peak is attributed to the wrist control (rotation) and a slow command is intended to the hand. The time window is adjustable.

- **Co-contraction:** a co-contraction of both the close and open muscles allows to switch from the hand command to the wrist command.



(a) (b)

Figure 2.8: Pouring with (b) and without (a) wrist rotation [39].

2.3 Future generation of myoelectric prostheses

Even though the improvements of the past 50 years have been huge, the most developed prostheses present a lack of intuitiveness. Indeed, as explained in the previous section, the control of prostheses such as Bebionic and i-Limb is tricky. A long period of training is needed to be able to use a complex prosthesis. A lot of ULA patients simply give up the training because of the lack of motivation to learn to use the device. However, the new generation of prostheses is becoming more and more intuitive.

In the human body, when the brain triggers a movement of the hand, the information goes through the nerves that activate the muscles (**Figure 2.9**). Groups of muscles are activated to produce a given movement, this is called a movement pattern (see **Section 1.1.3** about synergy). These patterns are specific to each person. After an amputation, the muscles can still be exploited. A map of the hand is printed inside the brain even after the limb is missing.

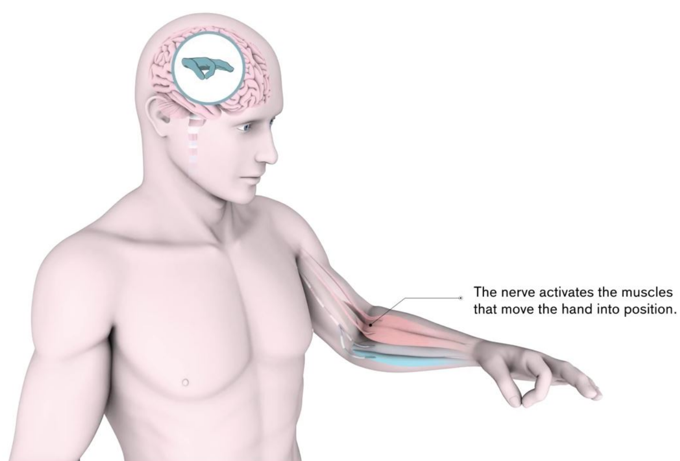


Figure 2.9: Muscle activation [41].

To be fully intuitive, a prosthesis should follow the same logic. This is not currently the case with the commercially available prostheses such as, for instance, the Bebionic

or i-Limb Quantum. These conventional transradial myoelectric prostheses only work with one or two electrodes and it requires tricky systems to switch between the different positions of the hand. This complexity is a barrier for many users.

The next generation of prostheses tends to work like a real arm and be more intuitive. It is based on the same principle as the human body. An example is the Adam's Hand developed by BionIT, see **Appendix E**. To understand the approach in detail, the Myo Plus pattern recognition system is described below (**Figure 2.10**). It was created by Ottobock and has been functional since 2019. This new system is compatible with prostheses such as Bebionic and Greifer hands. It has up to eight pairs of electrodes that are positioned around the arm [42]. The user has to imagine a movement of the hand and then the muscles of the residual limb are activated. The prosthesis receives the signals thanks to several electrodes placed on the stump. The information is then processed and an algorithm implemented inside the processor determines, on the basis of the signals received, which movement it consists in.

(a) (b)

Figure 2.10: Processing of the information captured by the electrodes (a), followed by the execution of the movement by the prosthesis (b) [41].

2.4 Virtual reality and upper limb prostheses

As seen earlier, myoelectric prostheses are quite complex devices. This is in part why ULA patients suffer high prosthesis rejection rate and are more susceptible to prosthesis abandonment than lower limb amputee patients [43, 44]. Indeed, the rehabilitation process surrounding the prosthetic prescription and training phases is long and grueling for the patients. To ease this process and avoid rejection of the artificial limb, prosthesis manufacturers and researchers around the world developed various virtual systems to help ULA patients.

These virtual systems may help with the prosthesis training for the patient, as well as the prosthesis assessing for the clinician and the prosthetist. Most commercially available virtual systems are based on a simple EMG biofeedback in order to train patients to use a myoelectrical prosthesis. EMG biofeedback virtual systems are useful to learn the basic functions of myoelectric prosthesis, which is to generate a muscle activity. However, this type of tool does not allow a deeper understanding

of the prosthesis.

A literature review from Dawson [45] in 2011 highlighted 3 other types of virtual system in adjunction to EMG biofeedback. These were serious game[1], 2D simulators and 3D simulators. Serious game controlled by EMG signals focuses on the entertaining component to help training the ULA patients. Yet, just as EMG biofeedback, it lacks the complex movement patterns of myoelectric prostheses. To simulate this complexity and allow the user to interact with a prosthesis by controlling it with EMG signals, various 2D and 3D simulators were developed and demonstrated in the literature. However, this review [45] only searched for virtual training systems to ease the rehabilitation process. Yet, if the rehabilitation process plays a significant part to avoid prosthesis rejection, choosing the right prosthesis may matter just as much.

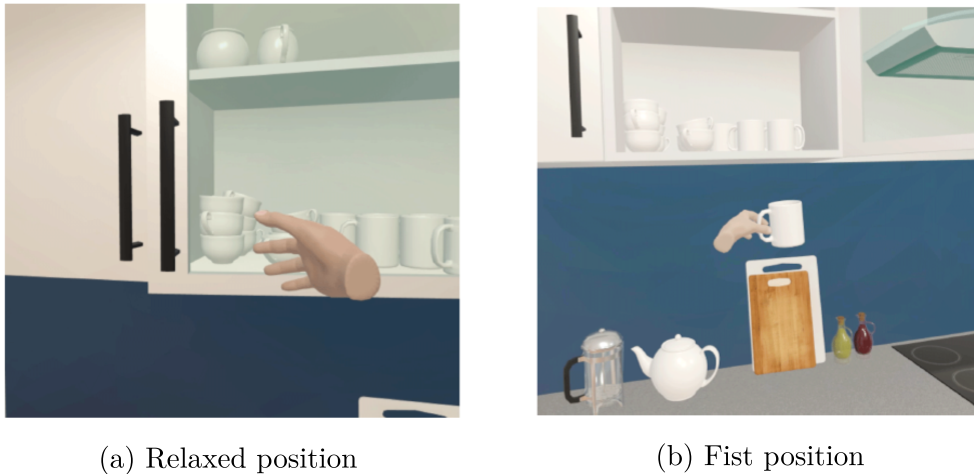
In order to discover most of the existing virtual systems available in 2020, a systematic scoping review was conducted by Ghazi, Lheureux and Ronsse [46]. It also discusses what are the pros and cons of each of these virtual tools.

This review showed that most studies designed their virtual system for a training purpose (98%; n=54) but none developed a prosthesis choosing application. It also showed that, on all the studies found, there were only 8 (15%) that used virtual reality (VR) as a displaying method.

Indeed, virtual reality is still an in-development technology, and it does not seem to have vastly spread yet, in the medical and rehabilitation domains. Furthermore, virtual reality is often wrongly defined in rehabilitation and medical research as any human-computer interaction [47]. However, there is a main difference between VR and simple display of virtual images in the "***sense of presence***" allowed by VR. This "sense of presence" is described by Sanchez-Vives and Slater [48] as the ability of the user to feel that he is "being physically present" in the simulation. Thus, it reproduces the closest feeling possible of reality inside a virtual environment and allows realistic responses from the user.

As the aim of this work was to develop a prosthesis choosing system for ULA patients to try different prosthesis in a virtual environment, it was then a major concern to create the *most realistic simulation*. Thus, it made sense to use an immersive virtual reality environment with a head-mounted display in order to provide this "sense of presence".

[1] A serious game is game which the primary purpose is not amusement, it has another purpose such as education, health care, etc.



(a) Relaxed position (b) Fist position

Figure 2.11: Hand grip patterns implemented in [49].

It is important to understand the pros and cons of the existing virtual reality systems in order to create a relevant virtual reality tool. On the 8 studies using virtual reality highlighted by Ghazi et al. review [46], 7 simulated only a hand opening and closing movement. The last study is from Nissler [49], and it appears to be the most advanced virtual reality system available. This virtual system claims 2 main features. Firstly, it provides 4 different hand gripping patterns (relaxed; fist; pointing; pinch) controlled by 8 EMG electrodes coupled with pattern recognition (**Figure 2.11**). And secondly, the strength of each of these hand gripping modes can be controlled proportionally to the amplitude of the EMG signal. This is illustrated in **Figure 2.12** where the increasing strength deforms the eyes of the piggy. These features are important to give the freedom to choose different grip patterns to accomplish a task, as well as precisely control the movement. However, if this virtual reality system may be helpful to train an ULA patient to use a myoelectric prosthesis, it does not simulate any specific and existing myoelectric prosthesis. Thus, it can not be used to help the patient to choose a prosthesis for his everyday use.

Figure 2.12: Proportional control of strength implies deformation of the virtual object [49].

This state of the art may confirm that the virtual tool developed during this work (see section 3) may be able to fill the gap in the literature by bringing both a prosthesis choosing application simulating existing myoelectric prostheses and a virtual reality display.

Chapter 3

Prototype

This chapter is divided in 4 parts. It begins with a re-contextualisation of the thesis with a detailed explanation of the aim and method. Secondly, the muscle computer interface is detailed, it is explained how the signals from the muscles are treated and sent to the computer. Then, the virtual environment built with Unity is presented. A last section explains how the prostheses were implemented virtually.

3.1 Requirements for this thesis

Currently when ULA patients have to choose their future myoelectric prosthesis, they do not have the opportunity to try it. So based on theoretical explanations, patients have to choose prosthesis that best suits them. However, the control and the logic used in theses devices are not always intuitive. This thesis is designed in order to propose an accessible tool for ULA patients so that they can test, in a virtual environment, commercially available myoelectric prostheses. This way, patients would be better able to understand the functioning of the prostheses and could thus more easily choose the prosthesis the most adapted to their needs.

The advantage of using Virtual Reality is the *sense of presence* that this tool provides (**Section 2.4**). Equipped with a VR Headset and controllers, the subjects are immersed in a virtual world and have the sensation to be physically present. This virtual tool brings the possibility to move around in an environment while interacting with virtual items. This is why it seemed to be fully relevant to use Virtual Reality to have the feeling to test real prostheses.

In this work, three different myoelectric prostheses were virtually implemented: Greifer, Bebionic and i-Limb hand, presented respectively in **Sections 2.2.1, 2.2.2 and 2.2.3**. The challenge was to model these three prostheses virtually so that they are as faithful as possible to the real ones. In the following setup, the right hand is considered as the prosthetic hand while the left hand as the valid one. The three myoelectric prostheses work by using 2 surface EMG electrodes, placed on the forearm of the patient, that catch the signals of the muscles. The signals allow to control the opening and closing of the prosthesis. Some tricks are also used to switch between the different grip patterns available, in the case of the Bebionic and i-Limb.

The virtual environment created in order to test the different prostheses was implemented with Unity Software. Some tasks were developed in order to test the different grip patterns of the prostheses and to interact with virtual objects inside the environment. The tasks highlight the different ways to control each prosthesis and aim to clarify the logic of the system used in each device.

This thesis is a proof of concept meaning that the aim is to demonstrate that the concept is feasible. As seen in **Section 2.4**, it is a pioneer project and, as far as we know, no other works have developed this idea yet. Before testing a prototype on real patients, it is first important to validate it on healthy subjects. This is why, in the context of this work, the virtual tool was designed for healthy subjects.

Setup Overview

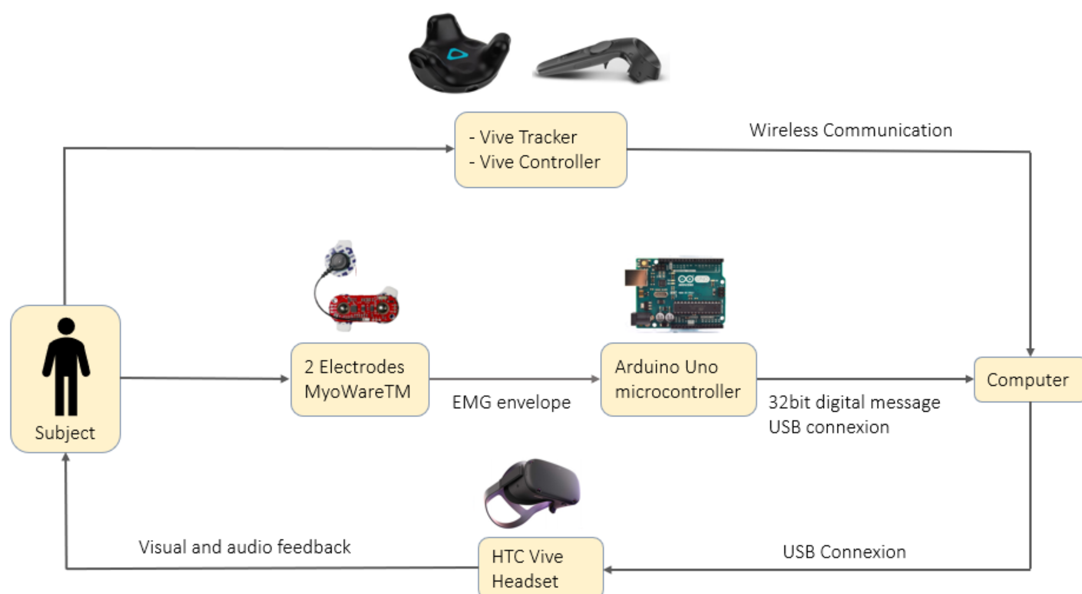


Figure 3.1: General overview of the setup organisation and its component devices. [50, 51, 52]

A general overview of our setup can be visualised in **Figure 3.1**. The myoelectric signals from the subject are caught by 2 EMG electrodes MyoWare^{TM}. They are then sent to the computer, via an interface using an Arduino Uno micro-controller. The Arduino Uno is a circuit board with a micro-controller and several input/output pins, allowing to run simple code processing signals. Once arrived in the computer, data is treated inside Unity software to control the virtual prostheses.
Two joysticks are used to track the positions of the right forearm and of the left hand: the Vive Tracker and Vive Controller. As the right hand is considered as the amputated one, the tracker is placed on the forearm near the elbow, at the end of the imaginary residual limb.

The HTC Vive headset provides a visual and audio feedback to the subject. These three Vive devices are located in space through two base stations placed in the VR room.

As it can be understood, the challenges to create such a tool were various. The **Table 3.1** resumes the identified requirements and the equipment needed for implementing the prototype. Each required block of the prototype is described in more details in the following sections.

	Requirements (Hardware)	Equipments
1	Interface to use the myoelectric signals of the subjects	Arduino + Electrodes (+ Computer)
2	Immersion of the subjects into a virtual environment	Head-mounted display + Base Stations (+ Computer)
3	Localisation of the **right** forearm in 3D space	Vive Tracker + Base Stations (+ Computer)
4	Localisation of the **left** hand in 3D space	Vive Controller + Base Stations (+ Computer)
	Requirements (Software)	Methods
1	The subjects become more qualified to choose a prosthesis adapted for them	Implementation of tasks
2	The subjects have the feeling to have the control on a real prosthesis	Implementation of the interaction between the prosthesis and the environment

Table 3.1: Resume of the main requirements for the developed tool.

3.2 Muscle Computer Interface

In this work, the same experimental setup is used for the 3 prostheses, the prototype board is displayed in **Figure 3.2**. Each component is then detailed in the following paragraphs. It should be noted that for the development, electrodes were replaced by potentiometers. The reason for this is that the gel from the electrodes should not be damaged during the development period. Output signals from the potentiometers can perfectly simulate the EMG signals. This picture of the real setup used can be found in **Appendix G.1**.

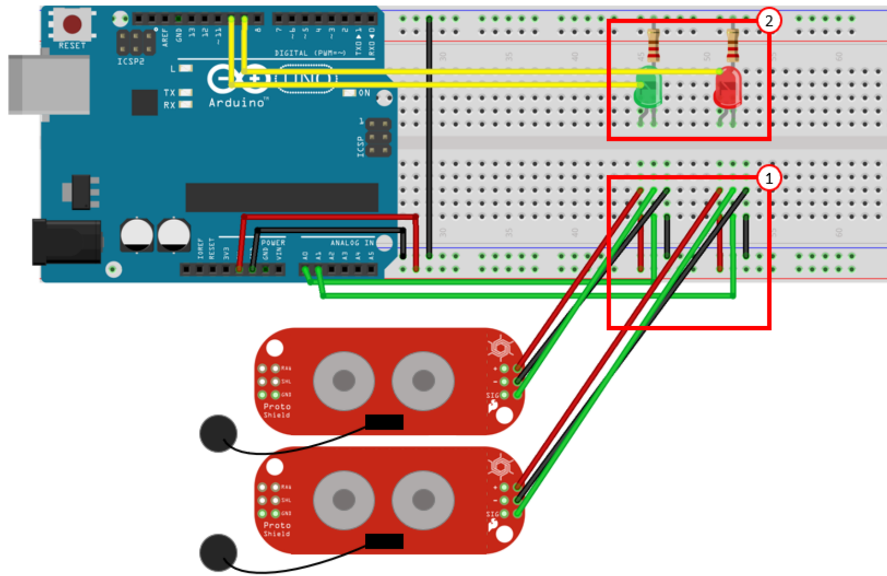


Figure 3.2: Illustration of the cleaned setup. (1) Electrode interface, (2) Feedback LEDs. Drawn with *Fritzing* Software.

3.2.1 MyoWare^{TM} electrodes

As it has been explained, the muscles of the human body are activated by small electrical signals. Each prosthesis has its own electrodes module, depending on the manufacturer. Nowadays, commercially available prostheses use bipolar surface dry electrodes. These non-invasive electrodes are easier to place and reduce the risk of infection due to chronic implantation.

Having wet bipolar electrodes available, the setup is built with **Covidien gel electrodes**. To interface the electrodes with the Arduino, a MyoWare^{TM} is used (**Figure 3.4**). The visible face of the electrode in **Figure 3.3** is snapped on the MyoWare^{TM}, and the other sticky surface is placed on the skin.

Figure 3.3: Covidien gel electrode [53]

.

Those MyoWare™ modules provide filtering, amplification, rectification and integration of the EMG signals. The output signal contains only the EMG envelope, defined as a continuous 0-5 V signal. Two MyoWare™ are required since two muscular activation zones are necessary for the opening/closing commands. Three electrodes are snapped on each MyoWare™, one for middle muscle, one for end muscle and one for reference zone (the ground). End muscle and mid muscle electrode snaps are spaced about 3cm apart while reference electrode snap is at the top of a 6cm length wire.

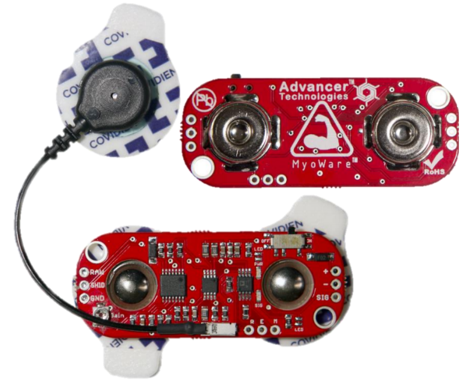


Figure 3.4: MyoWare™ electrode module [52]

3.2.2 Arduino Uno micro-controller

In order to ensure the interface between peripheral devices and the computer, an Arduino Uno is used (**Figure 3.5**). It was as a simple solution for a quick first prototype and is suggested by [52]. The Arduino Uno board uses an ATmega328 processor, providing 32 kilobyte (kb) of FLASH memory (for stocking flashed program), 2kb SRAM (Static Random Access Memory, for stocking variables during execution) and 1kb of EEPROM (Electrically-Erasable Programmable Read-Only Memory, for remembering variables despite a reboot). More importantly, Arduino Uno provides useful connections: among others 3.3V and 5V power supply, analogue inputs, digital inputs/outputs, Serial Peripheral Interface (SPI) and serial communication [50].

A summary of the connections is presented in **Table 3.2** and an illustration is presented in **Figure 3.5**. Electrode outputs (`emg0` and `emg1`) are connected to the **analog inputs** of the Arduino. The value is read as a 10bit digit. If the value provided by the electrodes exceeds a low threshold value (arbitrarily fixed at 1.5V), LEDs progressively light up via 8bit Pulse Width Modulation (PWM) outputs (marked by a "∼" in **Table 3.2**). Those are binary signals with a frequency of 500Hz, a voltage of 5V and an adjustable duty cycle.

Figure 3.5: Arduino Uno micro-controller [50]

+5	emg0, emg1	∼11	led1
gnd	all	∼10	led0
A0	emg0		
A1	emg1		

Table 3.2: Connections of the Arduino Uno pin's.
Yellow = Output, Green = Inputs. "gnd" is used for "ground".

.

3.2.3 Software implementation

The Arduino contains the program that transmits the data to the computer. Myoelectric signals, as explained before, are pre-filtered, integrated and amplified into the MyoWare^{TM} module. The resulting analogue signal is in the range of the supply voltage (namely 5V). This is illustrated in **Figure 3.6**. Amplified signals are conducted by wires to the Arduino controller. Analogue signals are read every 100ms and converted into a 10-bit digital signal. The delay should not be longer, as recommended by T.R. Farrell et al. in [54]. Otherwise, the subject could notice a lag. The received message is converted into a 8-bit message. The two 8-bit values are embedded into a 32-bit message (as presented in **Table 3.3**), containing all the information that could be sent to Unity. There is still room for supplementary information, like additional electrodes, buttons or orientation data.

If the received signal of the electrode 0 (resp. electrode 1) exceeds an arbitrarily low threshold (experimentally fixed at 1.5V for both electrodes), the exceeding value is converted into a 4-bit message and is sent to the LED 0 (resp. LED 1) for a first visual feedback. LED lighting allows to ensure that electrodes remains well connected.

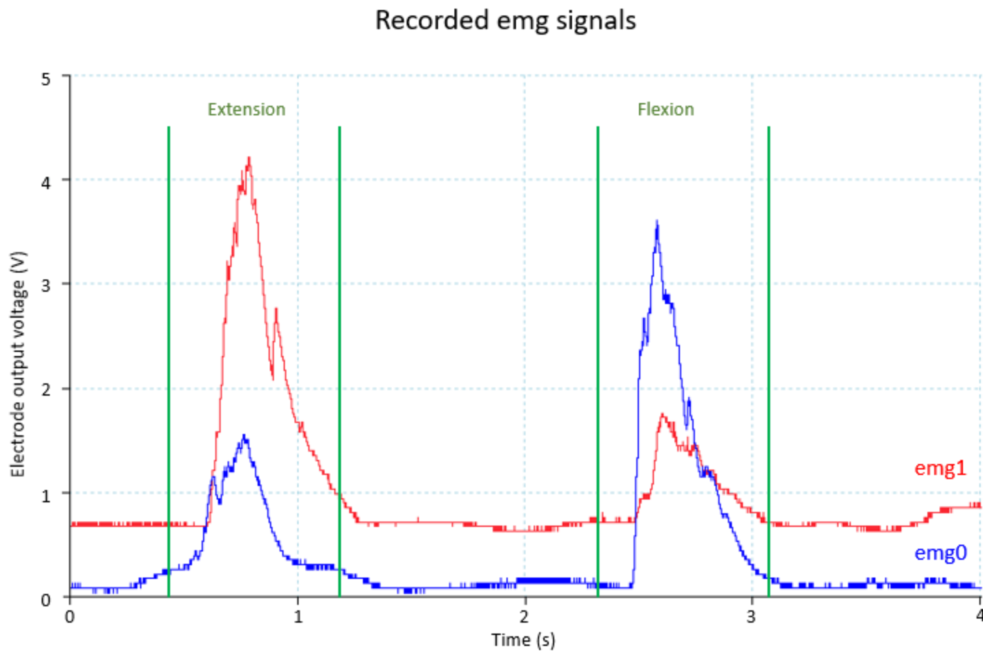


Figure 3.6: Example of signals acquired by the MyoWare^{TM} electrodes. Blue: Electrode 0 output signal, Red: Electrode 1 output signal. This graph was recorded by using an external measure device connected to the output electrode wire.

bit i	31	...	16 : 9	8 : 0
assigned message			emg1	emg0

Table 3.3: Allocation of the bits constituting the binary message sent to Unity.

3.3 Implementation of the Virtual Environment

First, in this section, the materials needed to immerse the subjects into the virtual environment are presented. An introduction to the Unity software is then made. Finally, the different game scenes implemented in our prototype are explained.

3.3.1 VR equipment

To immerse the subjects into a virtual environment, it is necessary to localise them, their gestures, and to provide them a realistic visual feedback. In this research, the **HTC Vive HMD** provides the head localisation, movements and image rendering. A **Vive tracker** module, attached with an armband, localizes the right forearm, considered as the end of the residual limb where the prosthesis should be attached.

Figure 3.7: Left hand modeled in VR, from SteamVR package.

The **Vive controller** is placed on the left hand and is attached, in the virtual environment, to a passive hand with the index finger pointing (**Figure 3.7**). The role of this hand is double. First it allows to interact with the prosthesis, to press buttons for instance, and secondly this left hand is used by the subjects to help their right prosthesis to perform the tasks.

Compared to the Vive tracker which only aims to be localized, the Vive controller offers more possibilities in terms of inputs and interaction with the real hand. But in the developed prototype it is only used for its localisation function.

Those 3 devices are illustrated in **Figure 3.8**. All this setup is installed in a special room. Two base stations are placed diagonally opposite each other at the top of that room and act like fixed references. They allow the localization of all the moving devices in the predefined space, by emitting infrared light. The HMD and the stations are connected by wires while the Vive tracker and the Vive controller remain totally free.

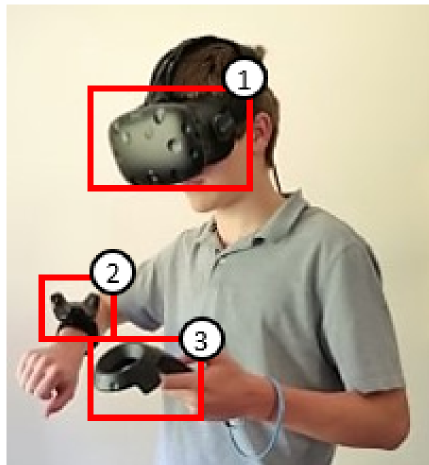


Figure 3.8: (1) HTC Vive HMD, (2) Vive tracker, (3) Vive controller.

3.3.2 Introduction to Unity Game Engine

Unity is a free platform intended to create video games. It is dedicated for both 2D and 3D games, whatever the complexity level. For example, it was used to develop video games such as *PokemonGo*, *Hearthstone: Heroes of Warcraft*, *Super Mario Run* and others [55]. An example of the editor frame is shown in **Figure 3.9**.

The game world is built in a scene, composed of elements called **Game Objects** (GOs). They can be created by the constructor or imported from available "asset packages". Those are kind of free/paid libraries that can be directly imported, containing models used to dress the scene (like a table, a car, a tree, etc).

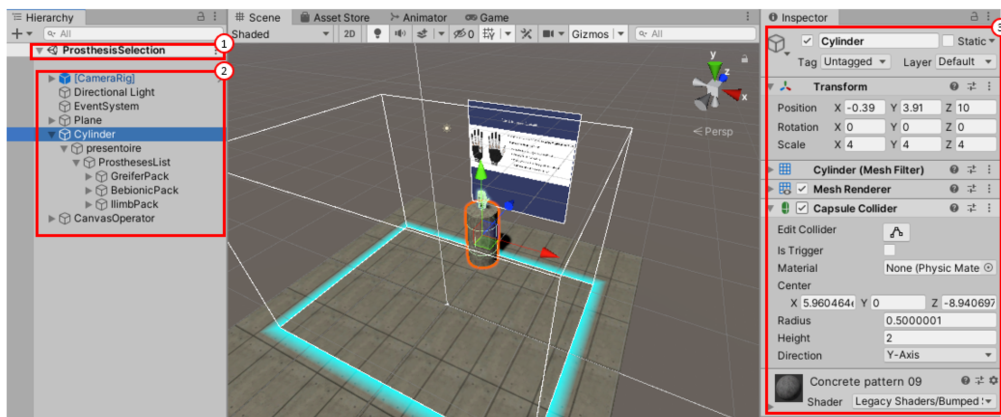


Figure 3.9: The unity editor framework. Example with the Prosthesis Selection Scene. (1) Scene Name, (2) Game Object Hierarchy, (3) Components of the blue-selected Game Object.

All the GOs possess several characteristics, called **Component**. A few of them are listed below.

– *Transform component*: determines the position, rotation, and scale of the object in the scene. All the GOs have it by default.

– *Rigid Body component* : enables the GO to act under the control of "real" physics, such as the Gravity.

– *Collider component*: used to detect or stop collision between GOs

– *Script component*: code in C# used to manually control the GOs. A script can be assigned to any GO, and can require references to other GOs or their components.

– Others such as component for texture, color, etc.

Among all the GOs, a **Camera** is required in order to give a visual feedback to the subject. The SteamVR package provides GOs and components necessary to interact with VR hardware. As an example, it contains a specific camera, moving according to the HMD position and orientation. It is called CameraRig, as written in blue at the top of the GOs list in **Figure 3.9**. The SteamVR package contains also components allowing a GO to follow the movements of the Vive devices.

A Game Object can have children GOs, just as a GO can be a parent of different GOs. When a GO has a parent, all the transform changes are performed with respect to its parent, instead of the game world. That is how the prostheses were implemented in this prototype. Each finger is a child of the main body of the prosthesis hand.

3.3.3 Game scenes

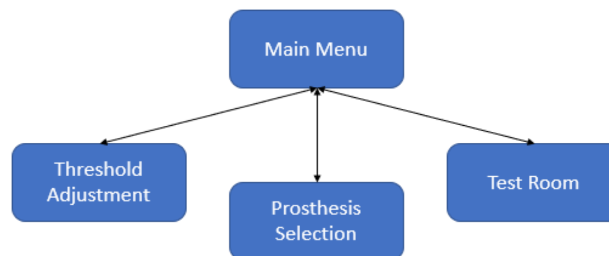
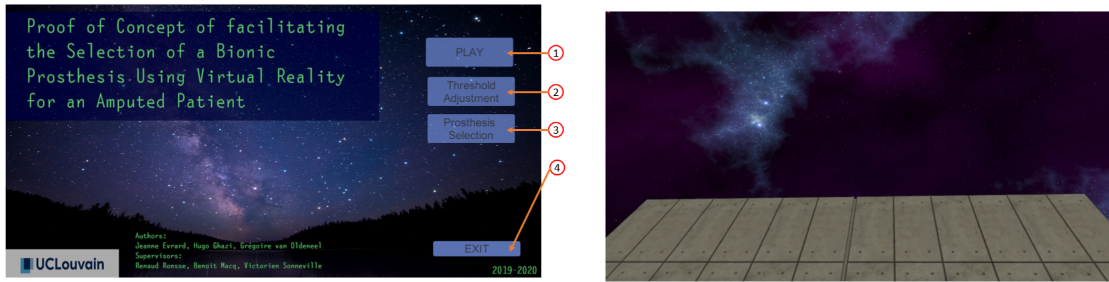


Figure 3.10: Game hierarchy overview. Each block represents a *scene*.

The use of the game requires an operator interacting with the computer screen, while the subject is immersed in the VR. The role of the operator is to select the scenes, scroll through the slides, adjust the threshold, etc. The game is divided into 4 scenes, as shown in **Figure 3.10**. Such a hierarchy is comparable to 3 rooms connected to a common corridor.
The structure of the different files of our project, can be found in **Appendix G.3**.

***Main menu* scene**



(a) Operator point of view. (b) Subject point of view.

Figure 3.11: Main menu display. It is required to pass through this scene to change room. Pointed frames in **Figure 3.11a** are the interacting buttons. (1) Access to the Test Room, (2) Threshold Adjustment Room, (3) Prosthesis selection Room, (4) Exit the application

The main menu is the central corridor containing all the doors to access the 3 other rooms. **Figure 3.11a** shows the view of the operators. Only the operators have access to the different buttons, allowing to launch the different child scenes. A script named `Option.cs` is attached to the operator dashboard; each button calls a public method contained in this script, which loads the specific scene corresponding to the button clicked. Each scene possesses its own independent game objects and variables. Nevertheless, it is possible to use common parameters between all the scenes. This can be done by saving them as user preference using a specific method.

While the operators are selecting the scene, the subject is immersed in a simple platform surrounding by a spacial view (see **Figure 3.11b**). This scene is used as a waiting room, allowing the subject to familiarize itself with the VR view. The HTC Vive HMD position and orientation is translated into the CameraRig GO position and orientation, allowing to adapt the view to the subject head movement.

***Threshold Adjustment* scene**

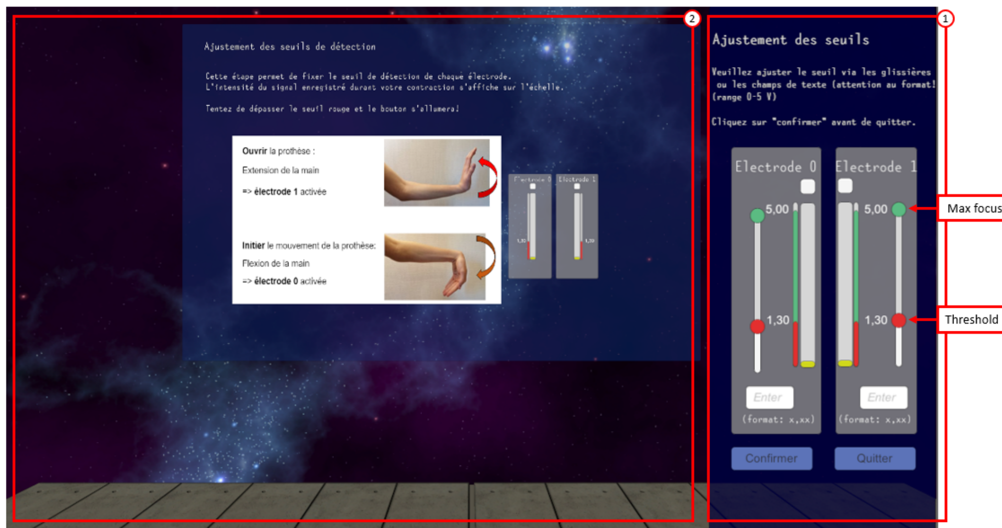


Figure 3.12: Threshold Adjustment : point of view of the operator. The subject point of view is visible in the background (2), while the dashboard (1) is only visible for the operator.

This is the first required step: adapt the program to the available signals emitted by the subject. The operator disposes of an interactive dashboard illustrated in **Figure 3.12 (1)**. The intensity of the received signal is displayed in real time on the yellow scale going from 0 to 5 Volts (in the figure, both signals are equal to zero). For each electrode, the minimal threshold is manually adapted by sliding the red handle or by encoding a float value. The green handle allows to focus the scale around the reachable value. This is used later to adapt the opening/closing speed of the prosthesis. If the signal goes beyond the threshold, the small light above the scale turns on. A feedback is provided to the subjects by displaying the intensity of the current emitted signals and the thresholds, see the gauges in **Figure 3.12 (2)**. Once the threshold is adapted, the operator presses the "Confirm" button which saves the threshold values.

All the scenes are commanded by only one script named `ThresholdManager.cs` attached to the GO of the dashboard of the operator, named CanvasOperator. This script reads the incoming message from the Arduino via a specific serial port. As a reminder, the structure of the incoming message was described in **Table 3.3**. A "read method" is charged to extract the 2 emg values from the received message. The same method is present in all the scripts requiring access to the emg values. When the operator saves the 2 thresholds and the two max focus values, these values become accessible in all the scenes. As explained in the previous section, those values are saved as user preferences and are named `"EMG0Threshold"`, `"EMG1Threshold"`, `"EMG0Max"` and `"EMG1Max"`. The operator can then quit the scene to come back in the *Main menu* using a "load scene" method.

Prosthesis Selection **scene**

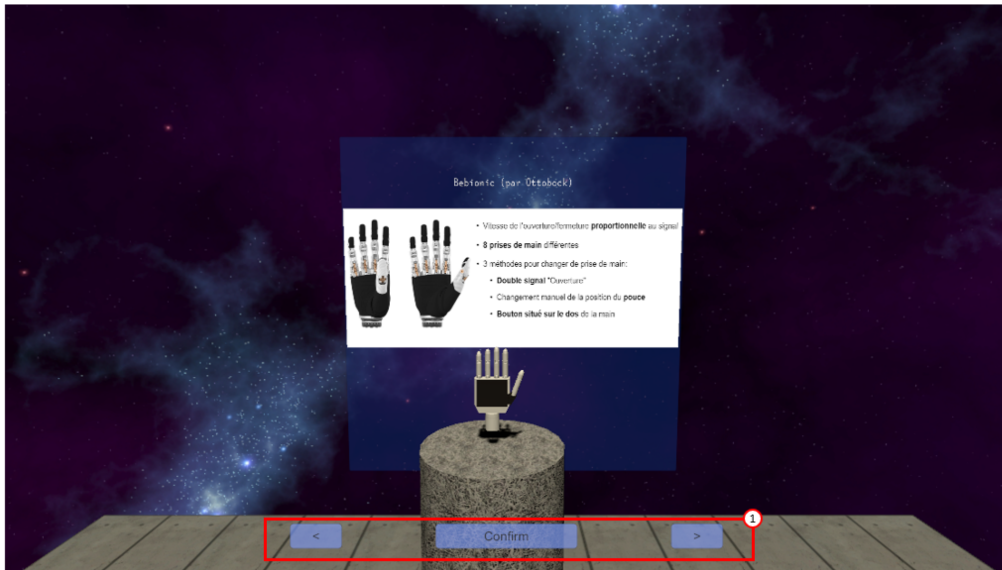


Figure 3.13: Prosthesis Selection : point of view of the operator. The subject point of view is the same, except the buttons (1).

This scene aims to select the prosthesis and to provide to the subject a quick review of its main features. As illustrated in **Figure 3.13**, the operator can switch of prosthesis by clicking on the right or left button. Each prosthesis and its explanation panel is contained in a specific game object. A partial view of this structure is shown in **Figure 3.9**. The left and right buttons activate the game object containing the prosthesis that has to be presented and disable the previous one (which becomes invisible). Once the desired prosthesis is presented, the operator has to click on the "Confirm" button which saves the index of the prosthesis as a player preference (like the saving of the threshold values).

Test Room **scene**

Figure 3.14: Test Room : point of view of the operator. The subject point of view is visible in the background (2), while the dashboard (1) is only visible for the operator.

This is the scene were the subject have the opportunity to virtually test the prostheses. As shown in **Figure 3.14**, the subjects have in front of them a table on which are placed some colored cubes of different sizes. Behind this table, a large panel supports explanation slides throughout all the session (not visible in the given Figure). The operator can keep an eye on the subject view and the electrode signals. The electrode signals display allows to continuously check that electrodes remain in place and that the threshold is adapted. The dashboard contains also buttons launching the explanation slides and then the task slides. Those slides will be presented further. Finally, a timer displays the cumulative time spent in this scene since it has been launched.

The table and the cubes possesses a *Collider* component and are subject to virtual gravity. Those objects interact with the prosthesis: they can be caught. For some tasks asked during the experimentation, the subjects use these blocks. The tasks are described more in details in **Section 4.4**.

The 3 prostheses GOs are Greifer, Bebionic and ILimb. Each prosthesis possesses its own controller script (namely `GreiferScript.cs`, `BebionicScript.cs` and `ILimbScript.cs`). Those scripts require the System IP Ports package to have access to the electrode data. Since only one active script can access the serial port of the Arduino in each scene, only one prosthesis GO can be activated at a time. The electrode intensity gauges, displayed in the operator dashboard in **Figure 3.14 (1)**, requires also the access to the EMG values. For the same reason, it is not possible to attach a new reading script to the dashboard. That is why prosthesis script is also responsible of the electrode intensity scales display. The specific control of each

prosthesis is described further in the following section.

3.4 Virtual prosthesis adaptation

Modeling a prosthesis implies to make some assumptions about the geometry or the command. Indeed, the design of real prostheses are protected by patents so all the information are not accessible. In this section, it is explained how the 3 prostheses - Greifer, i-Limb and Bebionic - and the forearm socket were built in virtual reality. We have modeled separately all the 3D parts of the models with Free CAD software. Afterwards, the different parts were assembled inside Unity.

For each prosthesis, the implementation logic of the control is explained. It is important to note that the Bebionic and i-Limb offer many different methods for controlling the grip pattern switch. This work focuses only on a few methods selected according to the differences between these two prostheses and depending on what could be achieved with the resources available.

3.4.1 Forearm socket

In real life, so that the prosthesis is fixed correctly to the remaining limb of the ULA patient, a forearm socket is designed and is really specific to the patient. In the virtual environment, a forearm compatible with the 3 implemented prostheses was designed with FreeCAD software (**Figure 3.15**). Thanks to this forearm, the subjects do not have the impression that the prostheses are flying freely in the environment.

Since the 3 prostheses are attached to the forearm, they are children of the ForeArm game object. The virtual position of ForeArm is given by its *SteamVR_Tracked Object* attached component. This component translates the real position of the Vive Tracker with respect to the 2 base stations into the virtual space.

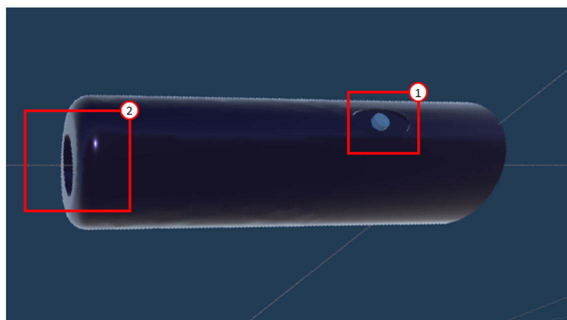


Figure 3.15: Virtual forearm prosthesis. (1) button to power on/off the prosthesis (2) prosthesis plug.

3.4.2 Greifer (Ottobock)

As in the real prosthesis (**Figure 3.16**), the Greifer modelling (**Figure 3.17**) is made up of one static part, connected to the prosthetic forearm, and of two mobile parts which form the clamp. This clamp opens and closes symmetrically, meaning that each part has always the same angle of rotation.
In the Unity environment, the Greifer model is then made up of 3 GOs. The two GOs representing the clamp are children of the third GO which is the part making the link with the forearm socket.

Figure 3.16: Greifer Hand, Ottobock [35].

Figure 3.17: Modelling of the Greifer prosthesis designed with FreeCAD software.

The functions of the Greifer implemented in VR are listed in **Table 3.4**. Basically, the clamp opens and closes thanks to the two electrodes: emg0 signal is responsible of the closing while emg1 signal is responsible of the opening. The strength of the emg signals are taken into account so that a proportional speed control can be implemented.
The real Greifer wrist can be rotated manually by the ULA patient. In order to implement this feature in VR, a detector placed on the wrist allows to activate the rotation by a simple touch.

Movement initiation	Action
Remark: the closing/opening speed is proportional to the signal intensity	
emg0 signal	Closing
emg1 signal	Opening
Wrist touched	Rotation of the wrist

Table 3.4: Summary of the features implemented for the Greifer prosthesis.

Algorithm 1 briefly resumes the main steps of the implementation of the prosthesis control. The script needs to access the serial port for getting electrode data and

to three specific GOs: WristDetector, TouchPadL and TouchPadR. These 3 GOs are each attached to a specific part of the prosthesis: WristDetector to the base of the wrist, TouchPadL and TouchPadR to the two extremities of the clamp. Their role is to detect when another object enters in contact with respectively the wrist or the extremity of the clamp. A specific script, named `Detector.cs`, is attached to each of these detectors. It sets a boolean variable to true when an object is detected and it gets the name of the penetrating GO.

The WristDetector is used to handle the rotation of the wrist. When the left valid hand touches the base of the wrist, the rotation is activated thanks to the script function `RotateWrist()`.
The two other detectors: TouchPadL and TouchPadR, allow to control the grasping of the objects. If both detectors are penetrated by the same GO, then this GO is caught and has to remains attached to the clamp. So that the GO follows all the translations and orientations of the clamp, it becomes temporarily a child of the clamp. The clamp is then no more able to close, avoiding to penetrate the object caught. The object is finally released if the clamp is open until one of the boolean values of the detectors turns to false. The object is then no more a child of the clamp.

The Greifer has some constrains regarding its closing and opening, there are limit angles. This is why the function `CheckCurrentAngle()` is implemented, its role is to control the current angle of the clamp. If this angle exceeds the limit angles, imposed for the opening or closing, the function corrects it and imposes to not go further.

Algorithm 1: Greifer script algorithm (pseudo-code)

```
Input: Serial port, WristDetector, TouchPadL, TouchPadR
Output: Manage Greifer movement
begin
    Get threshold values: threshold0 and threshold1;
    while Greifer is active do
        Read serial port and extract current emg0 and emg1 values;
        Display EMG values on the operator dashboard;

        ClampTouched = CheckDetector(TouchPadL, TouchPadR);
        WristTouched = CheckDetector(WristDetector);

        if (ClampTouched == False) then
            if (emg0 > threshold0) & (emg1 < threshold1) then
                CloseClamp (emg0);
        else
            Touched object attached;

        if (emg0 < threshold0) & (emg1 > threshold1) then
            OpenClamp (emg1);

        CheckCurrentAngle();

        if (WristTouched == True) then
            RotateWrist();
```

3.4.3 Bebionic (Ottobock)

The geometry of the Bebionic tends to look more like a real hand. **Figure 3.19** presents the 3D model designed with FreeCAD. Unlike the Greifer, Bebionic offers the possibility to switch between different grip patterns (**Section 2.4**).

Figure 3.18: Bebionic Hand, Ottobock [36].

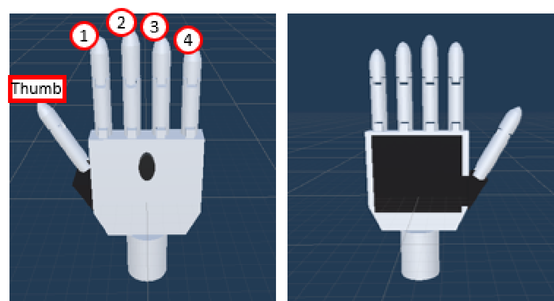


Figure 3.19: Modelling of the Bebionic prosthesis designed with FreeCAD software.

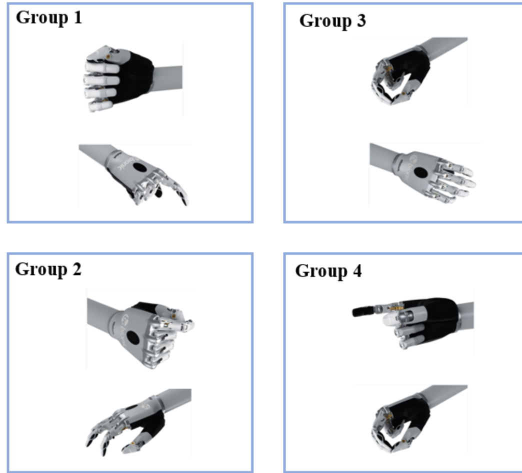


Figure 3.20: Bebionic grip patterns, divided into 4 groups.

The configuration by default implemented in the Bebionic proposes seven different grip patterns, with one grip pattern proposed 2 times. In total thus the patient has to switch between 8 grip patterns that are divided in 4 groups (**Figure 3.20**). The **Table 3.5** resumes the different ways to pass from one group to another. The simple closing and opening signals from emg0 and emg1 are kept to activate the movement itself. First inside a same group, 2 grip patterns are proposed. To switch between them a double signal of opening - emg1- is required. Note that to be able to change the grip mode, the prosthesis has to be in a fully open position.

Two positions of the thumb are possible: lateral position (Group 1 and 2) and opposition (Group 3 and 4). With the real prosthesis, the patient has to manually change the thumb position. Virtually, the subjects have to touch the base of the thumb with their left hand. When the subject is located in Group 1 or 2, this command allows to pass to Group 3. In the other way, when the subject is located in Group 3 or 4, this command allows to pass to Group 1.

The last Grip change explained in **Table 3.5** is the button located on the back of the hand. When the button is pushed by the left hand, it allows to pass from Group 1 to Group 2 and vice versa, or from Group 3 to Group 4 and vice versa.

Movement initiation	Action
Remark: the closing/opening speed is proportional to the signal intensity	
emg0 signal	Closing
emg1 signal	Opening
Grip change initiation	Action
Remark: a grip change can occur only if the prosthesis is in its initial position meaning fully open.	
Double emg1 signal	Grip pattern change inside a same group
Top button pressed	Group change
Base of the thumb touched	Group change: switching from opposition to lateral (vice versa) position of the thumb

Table 3.5: Summary of the features implemented for the Bebionic prosthesis.

To fully understand the architecture of the virtual model of the Bebionic Hand, the hierarchy of the Bebionic GOs is illustrated in **Figure 3.21**. Each object was built independently in the Free CAD software and then put together inside Unity.

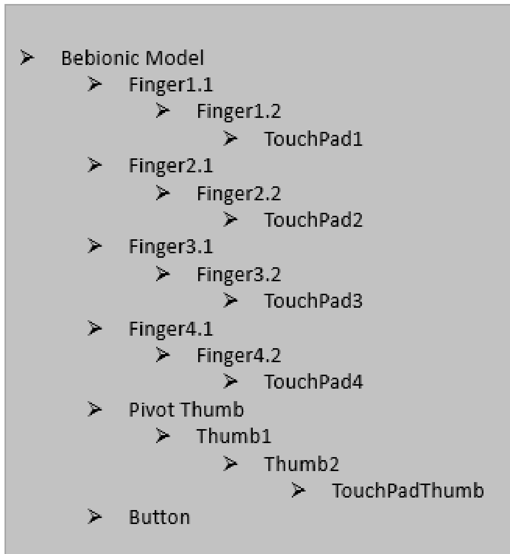


Figure 3.21: Simplified hierarchy of the Bebionic GOs.

The Bebionic prosthesis is composed of one main GO for the palm (BebionicModel) which is the parent to all the other GOs that compose the hand prosthesis. There is one GO for the thumb basis articulation (PivotThumb), represented by the black part at the basis of the thumb in **Figure 3.19**. There is also one main GO for each finger and a last GO for the black button on the top of the hand (Button). The finger i is composed of 2 phalanges j, with one GO for each of them (Finger *i.j*). One more GO is attached at the top of each finger: TouchPad *i*. It has exactly the same role that the TouchPad detectors explained in the Greifer previous section.

An overview of the algorithm is presented in **Algorithm 2**. There are several inputs required for this main function: the Serial port for getting the electrodes data, FingerDetectors, ThumbBasisDetector and ButtonDetector. The FingerDetectors comprise all the detector components coming from the TouchPad of the 5 fingers, informing about the penetration of a GO. The function `CheckDetector()` is used in order to see if the detectors have been touched by an external object.

The ThumbBasisDetector and ButtonDetector are used to implement the change grip, as explained above in **Table 3.5**. When these detectors are touched by the left hand implemented in VR, boolean values ThumbOppositionFlag and ButtonFlag are changed, which allows to change group. The function `MovementOfTheThumb()` implies the change of the thumb position from opposition to lateral or vice versa. To switch inside a same group, an "if statement" checks if a double quick opening signal is emitted (emg1 intensity should quickly exceed the threshold two consecutive times). If it is the case, the GripSet boolean value changes.
By knowing the states of these 3 boolean values - ThumbOppositionFlag, ButtonFlag and GripSet - the grip selected is determined. The grip pattern activated is given by the function `GiveGrip()`.

In order to implement a grip pattern, the logic of implementation is to assign a list of limit angles for each GO. The GO stops to rotate once it has reached its final angle. When all the GOs have reached their limit angle, the grip pattern is reproduced. So to have 8 grip patterns available, 8 lists containing the limit angles for each object are created. This is the role of the function `CheckCurrentAngle()`, the argument is the Grip which be equal to a digit between 1 and 8. This way, the function knows which Grip pattern it has to reproduce.

To handle the grasping of an object the FingersDetector are used. Amongst the 8 grip patterns available, only one allows to grasp an object: Tridigital pinch. An object is considered as being caught if it touches the thumb and at least one of the two next fingers at the same time, while the activated grip is Tridigital pinch. Then, the hand can no more be closed to avoid unrealistic object penetration.

Algorithm 2: Bebionic script algorithm (pseudo-code)

```
Input: Serial port, FingerDetectors, ThumbBasisDetector, ButtonDetector
Output: Manage Bebionic movement
begin
    Get threshold values;
    Encode the angles of the 8 grip patterns into lists;
    while Bebionic is active do
        Read serial port and extract current emg0 and emg1 values;
        Display EMG values on the operator dashboard;
        FingersTouched = CheckDetector(FingerDetectors);
        ThumbBasisTouched = CheckDetector(ThumbBasisDetector);
        ButtonTouched = CheckDetector(ButtonDetector);
        /* Check commands                                        */
        if (ThumbBasisTouched == true) then
            ThumbOppositionFlag= !ThumbOppositionFlag;
            MovementOfTheThumb(ThumbOppositionFlag);
        if (ButtonTouched == true) then
            ButtonFlag = !ButtonFlag;
        if (Double emg1 signal while opened) then
            GripSet = !GripSet;
        Grip = GiveGrip(ThumbOppositionFlag, ButtonFlag, GripSet);
        /* Prosthesis movement                                   */
        if (FingersTouched == False) then
            if (emg0 > threshold0) & (emg1 < threshold1) then
                CloseTheHand (Grip, emg0);
                CheckCurrentAngle(Grip);
        else
            if Grip == Tridigital pinch then
                Touched object attached;
        if (emg0 < threshold0) & (emg1 > threshold1) then
            OpenTheHand (Grip, emg1);
            CheckCurrentAngle(Grip);
```

3.4.4 i-Limb Quantum (Össur, Touch Bionic)

The i-Limb Quantum model, illustrated in **Figure 3.23**, is exactly the same 3D model than the one built for the Bebionic. The only differences are the colors used.

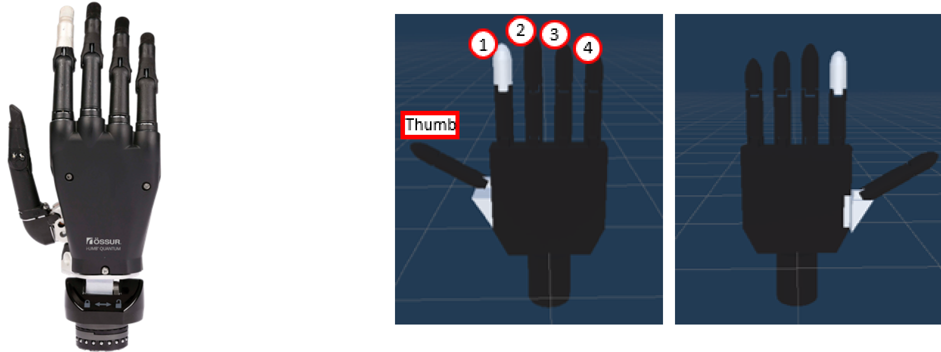


Figure 3.22: i-Limb Hand, Ossur [56].

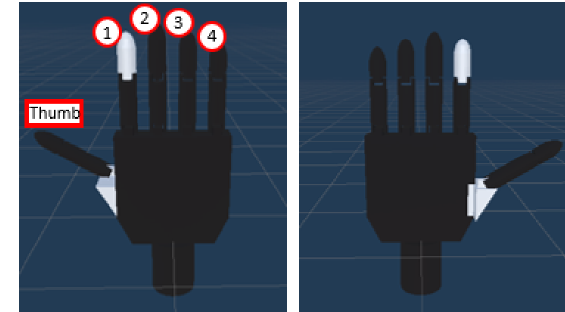


Figure 3.23: Modelling of the i-Limb prosthesis built with Free CAD software.

Unlike the Bebionic, there is no default mode proposed for the i-Limb. Concretely the initial mode is adapted to each patient. So we made the choice to implement 5 different grip patterns. Two methods are used to have access to these 5 patterns: the **gesture control** and the **proximity control** (**Figure 3.24**). These 2 methods to change the grips have been explained in **Section 2.2.3**.

The gesture control consists in moving the prosthesis in one of the 4 directions assigned in space after having triggered the jump of the index. The direction change has to be quick and right after the index jump. In order to have a jump of the index, it requires a maintained opening signal (see **Table 3.6**). To each direction (left-right-top-bottom), a position is assigned.

The second method implemented is the proximity control (left side of **Figure 3.24**). If the prosthesis goes fairly close over this chip, a new grip pattern is activated. In the virtual game implemented, the Grip Chip gives access to the "MouseGrip" which consists in a position allowing to grasp a computer mouse.

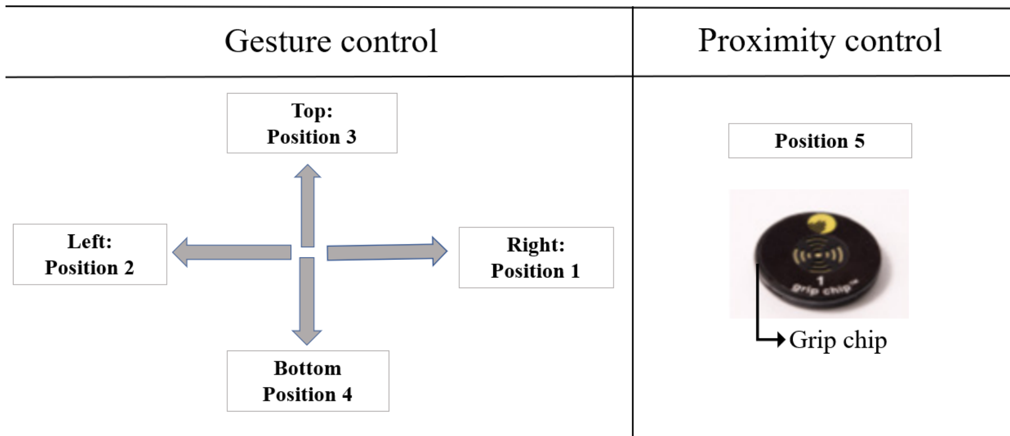


Figure 3.24: Overview of the implemented i-Limb control. Four grip patterns are accessible by motion (left side) and one grip pattern is assigned to the proximity grip chip [56] (right side) .

The functions are listed in **Table 3.6**. To activate the movement, it works exactly as the Greifer and the Bebionic, it uses the emg0 and emg1 signals.

Movement initiation	Action
Remark: the closing/opening speed is proportional to the signal intensity	
emg0 signal	Closing
emg1 signal	Opening
Grip change initiation	**Action**
Remark: a grip change can occur only if the prosthesis is in its initial position meaning fully open.	
Maintained emg1 signal	Jump of the index then move of the prosthesis in one of the 4 directions (left-right-top-bottom)
Proximity grip chip	Passing the prosthesis above the grip chip

Table 3.6: Summary of the features implemented for the i-Limb Quantum prosthesis.

The implementation of the i-Limb control is briefly resumed in **Algorithm 3**. The inputs are SerialPort, FingerDetectors and ForeArmPosition. To handle the grasping of objects it is exactly the same method than the one used for the Bebionic, this is why it will not be re-explained. The command part does not require any buttons, only emg1 signal and motion of the forearm are used to control the grip change. The ForeArmPosition is given by the position of the Vive tracker placed on the forearm's subject. The function `GiveGrip()` calculates the main direction in which the forearm has moved, and assigned the corresponding grip.

Algorithm 3: i-Limb script algorithm (pseudo-code)

```
Input: Serial port, FingerDetectors, ForeArmPosition
Output: Manage i-Limb movement
begin
    Get threshold values;
    Encode the angles of the 5 grip patterns in lists;
    while i-Limb is active do
        Read serial port and extract current emg0 and emg1 values;
        Display EMG values on the operator dashboard;
        FingersTouched = CheckDetector(FingerDetectors);
        /* Check commands                                  */
        Get current position;
        if Prolonged emg1 signal while already fully opened then
            Jump of finger1;
            Grip = GiveGrip(Position);
        if Passed above the grip chip then
            Grip = MouseGrip;
        /* Prosthesis movement                             */
        if (FingersTouched == False) then
            if (emg0 > threshold0) & (emg1 < threshold1) then
                CloseTheHand (Grip, emg0);
                CheckCurrentAngle(Grip);
        else
            if Grip == Tridigital pinch then
                Touched object attached;
        if (emg0 < threshold0) & (emg1 > threshold1) then
            OpenTheHand (Grip, emg1);
            CheckCurrentAngle(Grip);
```

Chapter 4

Pilot experiment: Materials and Method

This chapter aims to explain the process used to test our prototype. It begins with the study design, followed by a listing of the equipment needed and a explanation of the room installation. The electrode placement is part of this section as well. Afterwards, the two methods to evaluate the subjects are explained in details. Then, the experiment protocol is presented, it includes the guidelines to follow in order to complete the experiment. Finally, the variables of this study are highlighted.

4.1 Study design

This pilot experiment is a case series study. Methodology was prepared following guidelines from the STROBE checklist [57, 58].

Settings

Experiment took place on May 21 and 22, 2020. Due to Covid-19 measures, most university premises were still on lock-down at the time of the experiment, thus it was conducted safely at home.

Participants

As it is a pioneer project, before testing the prototype on ULA patients, it was first important to validate it on healthy patients. This is why this study was focused on testing healthy subjects.
Due to the sanitary crisis, the experimental setup has been only tested on 5 available subjects who where healthy family members of one of the authors. Considering this, there were no recruitment methods or inclusion and exclusion criteria.

4.2 Equipment and room installation

Experiment was performed in a room equipped with a table and a chair where the participants were seated at. Needed experimental hardware consisted of a HTC

Vive head-mounted display, Vive tracker, Vive controller and two base stations (**Section 3.3.1**). Also it required an high-end computer and finally an in-house built EMG controller composed of MyoWare electrodes coupled with an Arduino Uno micro-controller (**Section 3.2**). The computer used was an *Acer* laptop Aspire7, details are given in **Appendix G.2**.
Two base stations were placed in the room in order to localize the VR devices. In the ideal setup, they are placed in two opposite corners of the room, with a maximum distance of 5 meters between. The ideal height is 2 meters and the stations have to be angled down by 30-45 degrees.

The computer and the interface equipped with the Arduino were placed on the table. The chair where the subjects were sitting was placed approximately 0.4m in front of the table. So that the subjects were free to perform movements without being bothered by the table (**Figure 4.1**).

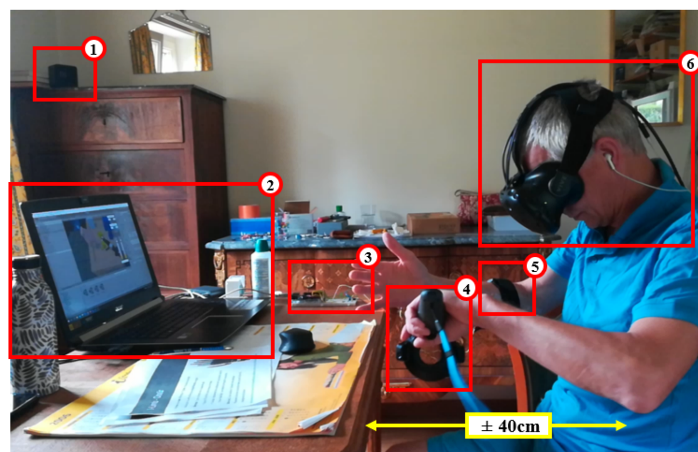
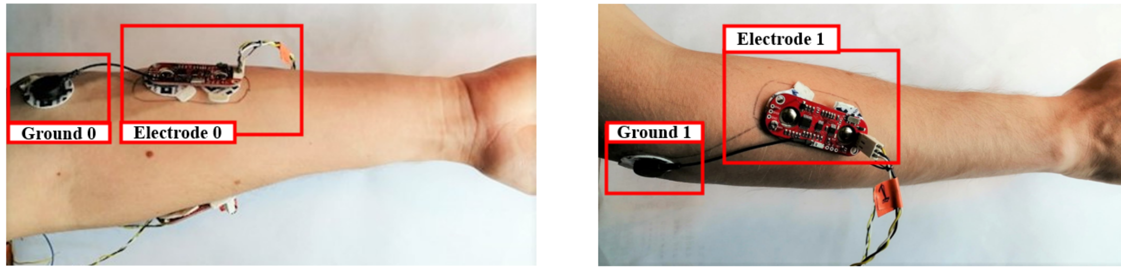


Figure 4.1: Global view of the setup (1) One of the two base stations (2) Computer used to run the virtual environment (3) Board fitted with the Arduino, linked with the electrodes by wires (4) HTC Vive Controller (5) the two electrodes covered by the HTC Vive Tracker (6) HTC Vive head-mounted display and headphones

Electrode placement

To prepare the arm before putting the electrodes, it was necessary to quickly clean the zones with an hydroalcoholic solution. One bipolar EMG electrode was placed on the extensors of the wrist, and another was placed on the flexors of the wrist (**Figure 4.2**). Meanwhile, the reference electrodes were respectively placed on the medial and lateral epicondyle of the humeral bone.



(a) Electrode 0 placed on the flexors of the wrist

(b) Electrode 1 placed on the extensors of the wrist

Figure 4.2: Placement of the two electrodes on the right forearm of a subject.

There is no standard location to place electrodes since placement is specific for each patient. Following the SENIAM guidelines [59], bipolar surface sensors should be placed at a point somewhere along an imaginary line between two anatomical muscle landmarks. Factors for a good location are the presence of motor points, muscle tendons, and other active muscles near the EMG sensors. A "trial and error" approach was used to find a good and stable EMG along this imaginary line. Concerning the reference electrode, it need to be placed on an electrical inactive tissue such as a bone in order to minimize the risk of disturbance with the bipolar electrode placed on the muscle.

4.3 Evaluation methods

The subjects were assessed in two different ways. First, a survey was proposed in order to see the impact of testing virtually the prostheses. The subjects had to fill two times the survey, one time before the VR session and the other time after. The aim was to evaluate the potential change of vision that the subjects had of the 3 prostheses.
The second evaluation method consisted in performing virtual tasks. The subjects had to performed 3 tasks with the prostheses and each task was timed.

Method 1 : Survey

The survey can be seen in **Appendix H.1**, questions can be grouped into different categories.

- Personal information: the subjects had to give their age, their profession and if they were left or right-handed.
- Prostheses classification according to general criteria (from Q3 to Q14): the subjects had to classify the 3 prostheses for each criteria. In total, 6 topics were proposed: the aestheticism, functionality, robustness, intuitiveness, innovation and motivation to learn. For instance, the subjects had to say which prosthesis was, according to them, the most and the least robust among the Greifer, i-Limb and Bebionic. Each question was duplicated so that it could be seen if the subjects answered randomly or not, which leads to a total of 12 questions.

- Activity-based questions (from Q15 to Q17) : for each of the 3 prostheses, the subjects had to check the activities they would be comfortable to do with this given prosthesis. There were 8 activities proposed: eat, dress, use a phone, shop, cook, clean and maintain a house, do the laundry and travel (bike, car, ..).
- Ending question (Q18): the question was about the final choice of the subjects, to know which prosthesis they preferred. The subjects had also the possibility to give general remarks at the end.
- Impact of VR (Q19): this question was only asked in the second questionnaire.

Method 2 : Tasks

All the instructions of the tasks can be found in **Appendix F.2**. Each task was timed, the timer was initiated once the task explanation was finished.

- **Task 1 : Exploring the prosthesis control (Only for Bebionic and i-Limb).**
  Subjects had to reproduce the hand position that was displayed on the slide. It did not concern the Greifer given that there is no grip change to test. Clear guidelines were written so that the subjects knew how to change the grip patterns. In total, there were for both prostheses, 5 grip patterns to reproduce. Once a grip pattern was well completed by the subjects a "Congratulations" flag appeared. To prevent subjects from getting lost, an interactive panel was displayed on the back with current group/grip pattern activated by the prosthesis (**Figure 4.4**).
- **Task 2: Manipulating objects.**
  The subjects had to interact with virtual blocks placed on the virtual desk. The aim was to build a castle made of 6 blocks of different size and shape (**Figure 4.3**). To perform this building, the good grip pattern had to be activated.

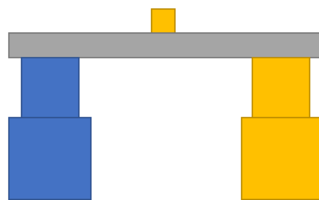
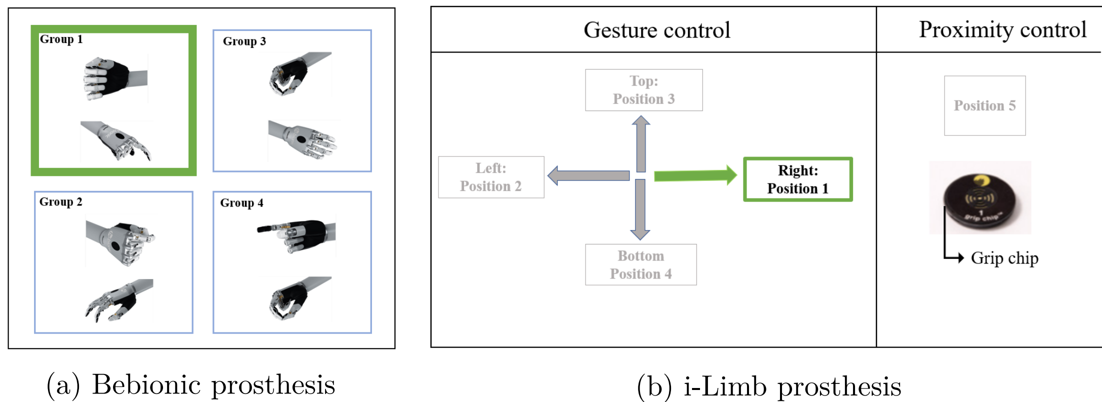


Figure 4.3: Castle made of blocks.

- **Task 2b: One change grip (for Bebionic and i-Limb) + interaction with an object.**
  In order to have a task where the subjects were asked to both interact with objects and to change the grip pattern (in the case of the Bebionic and i-Limb),

the Task 2b was performed. Once the castle was built, it was asked to the subjects to push the smallest cube without collapsing the whole castle. With the i-Limb and Bebionic, the subjects had to change the grip pattern and to select the one with the pointing index finger. With the Greifer, the subjects simply had to drop the little cube.



(a) Bebionic prosthesis

(b) i-Limb prosthesis

Figure 4.4: Interactive control map : the green frame indicated the group (a) or the grip pattern (b) activated by the subjects.

4.4 Experiment protocol

An overview of the experiment is listed below, followed by a detailed explanation of each step.

- Brief presentation of the experiment
- Theoretical explanation of the 3 prostheses
- Electronic opinion survey: First session
- Setup installation
- VR session: Task performance with the 3 prostheses
- Electronic opinion survey: Second session

Each subject was tested one at a time, and the required time to perform the experiment was approximately 1h-1h30 per person.

1. Brief presentation of the experiment

First it was important that the subjects understood clearly the aim of the project. During approximately 5 minutes, the general context in which the ULA patients have to select their future prosthesis was explained.

2. Theoretical explanation of the 3 prostheses

The purpose of the step was to simulate the presentation of the prostheses made by the manufacturers to the ULA patients. Each prosthesis was explained one by one with a presentation slide as support. For instance, the slide used to present the Bebionic is displayed in **Figure 4.5**. This slide was only a support, in addition the examiners explained a lot orally. Later, when the subjects had to fill the survey, the paper slides helped them to classify the prostheses.

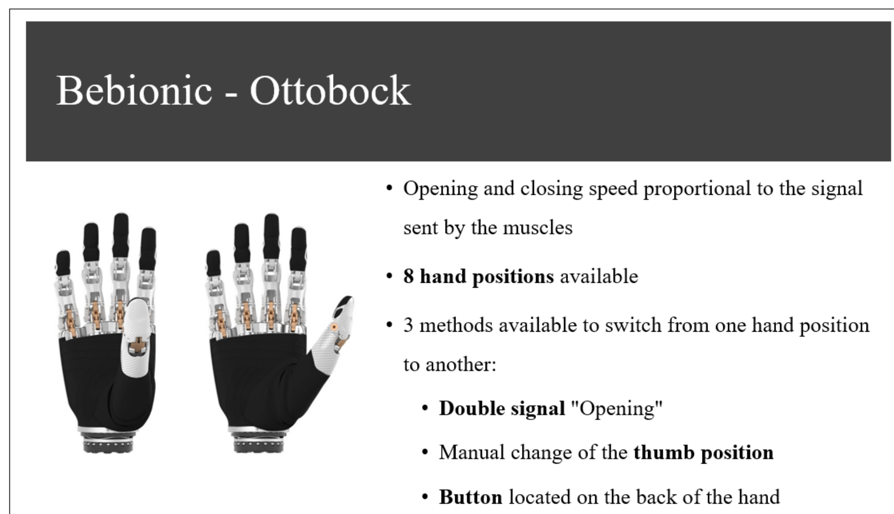


Figure 4.5: Presentation slide of the Bebionic Hand.

After the presentation of the prostheses, a brief video, made directly by the manufacturer (namely Ottobock or Ossür) was shown. This way, the subjects could visualise the prostheses used in daily life by ULA patients. For instance, it could be seen a man working on his computer or tying his shoelaces with the prosthesis. The slides and the video links of each prosthesis can be found in **Appendix F.1**.

3. Electronic opinion survey: First session

After having a first impression, subjects were asked to fill, for the first time, the questionnaire (see **Appendix H.1**).

4. Setup installation

Hardware placement: Once the questionnaire was completed, the EMG electrodes were placed on the forearm, the guidelines were presented in **Section 4.2**. So that the electrodes were completely fixed, some medical tape was placed on the top of them. Then, the **Vive tracker** was placed on the EMG electrodes, around the arm thanks to the armband adjustable to the size of the arm. Subjects were asked to remain seated on the chair to avoid problems with the electrode wires.

Movements explanation: Once the electrodes and the Vive Tracker were fixed, the examiners explained the specific movements to activate the electrodes (**Figure 4.6**). Only two movements were required to have a complete control of the 3 prostheses: flexion and extension of the hand. As soon as the two movements were assimilated, the immersion in VR could start and the head-mounted display was placed on the subjects (**Figure 4.1**).

Figure 4.6: The two movements performed by the subjects. Flexion (resp. extension) of the hand to activate electrode 0 (resp. 1).

Threshold adjustment The first scene where the subjects were immersed was the *threshold adjustment* one (described in **Section 3.3**). The thresholds were set one at a time. After a few repetitions of each movement, the thresholds were correctly adjusted.

The subjects could see directly the electrode gauges (**Figure 3.12**). Thanks to this virtual visual feedback, subjects had the opportunity to observe the impact of their own muscle contractions on the signal intensity. It was important to spend some time to let the subject become familiar with the environment and the signals.

The threshold adjustment was a crucial step because if the 2 thresholds were not perfectly adjusted then the subjects would have much more troubles to perform correctly the tasks.

5. VR session: Task performance with the 3 prostheses

The subjects were then ready to start the tasks. They were divided into two groups according the order in which they had to test the prostheses (**Table 4.1**). For convenience, all subjects started with the Greifer considering that it was the easiest one in order to become familiar with the opening/closing system[a].

Group \Order	1	2	3
Group 1	Greifer	i-Limb	Bebionic
Group 2	Greifer	Bebionic	i-Limb

Table 4.1: Order in which the prostheses were tested.

Each prosthesis was tested one after the other. The procedure was similar for the 3 prostheses (a summary of the planning is displayed in **Figure 4.7**):

- Selection of the prosthesis in the *Prosthesis Selection Scene* (see **Section 3.3.3**).
- Immersion of the subjects in the *Test Room*. The aim of this first step was to explain the control of the prosthesis. Few slides were displayed in the background of the scene so the subjects could read while the examiners were explained orally (all the slides are gathered in **Appendix F.2**).
- Task 1 (only for Bebionic and i-Limb): Once the control was understood by the subjects, task 1 performance could start. The timer was started once the task was explained, and stopped when the last "Congratulations" flag appeared.
- Task 2 (for the 3 prostheses): The timer was started once the task was explained, and stopped when the castle was entirely built.
- Task 2b (for the 3 prostheses): The timer was started once the task was explained, and stopped when the small cube dropped.

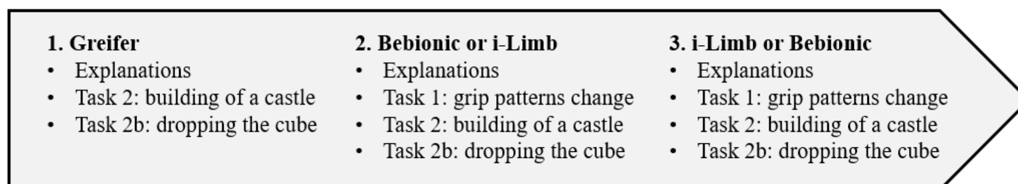


Figure 4.7: Timeline of the VR session.

General remarks:

- Initially, the thresholds were set higher because the subjects could not emit proper signals, the two signals were not independent enough. Once the subjects got used to it, thresholds were readjusted.
- During all the tasks execution, the examiners had to pay attention that the subjects did not do too sudden movements which could damage the electrodes wires.
- To perform these actions, it required a lot of effort from the subjects, sometimes breaks were needed between the tasks so that the subjects' arms could rest.

6. Electronic opinion survey: Second session

The final step was to fill the same questionnaire that the subjects had before the immersion in VR. One extra question was asked: "Did the training in virtual reality help you in the choice of the final prosthesis? ".

[a] The only difficulty of the Greifer was to manage the activation of the movements, there was no grip patterns change. In a real rehabilitation process, controlling the opening/closing is the first task to master [39].

4.5 Variables

Outcomes

Main dependent variable in this study was the participant subjective opinion about each prosthesis. Second dependent variable was the completion time for each task.

Exposure

Are considered exposure variable both the detailed prostheses characteristics explanation and the VR session. Indeed, it was hypothesized that those two variables would have an effect on the subjective opinion variable.

Potential effect modifiers and/or confounders

Immersion fidelity may be a potential confounder as this pilot VR system may not yet reproduce perfectly a real-life prosthesis. Participants may also be a potential confounder as they were chosen with no criteria due to the Covid-19 pandemic.

Chapter 5

Results

This chapter presents the results obtained during the experiments. First, personal information of the subjects is summarised. Then, the presentation of the results is divided into two parts: the different timings obtained for the tasks and then the survey responses.

5.1 Subjects

The experimental setup has been tested on 5 subjects. Their profiles are resumed in **Table 5.1**.

	Group 1			Group 2	
Subjects	1	2	3	4	5
Gender	F	F	F	M	M
Year of birth	1998	1999	1972	2002	1966
Profession	Student	Student	Housewife	Student	Music Teacher
Left-handed or right hander	Right	Left	Right	Right	Right

Table 5.1: The profile of the subjects.

The subjects were split into two groups according to the order in which they have tested the prostheses (**Table 4.1**). Group 1 tested the prostheses in the following order: Greifer, i-Limb and then Bebionic. Whereas Group 2 tested in this order: Greifer, Bebionic and i-Limb. Subjects took part in the experiment in the following order: 1, 4, 2, 5 and 3.

5.2 Task results

Table 5.2 briefly reminds the 3 tasks. The results of Task 1 and Task 2 are exposed for each prosthesis. Results of Task 2b are only displayed in **Section 5.2.4**.

Task	Description
Task 1	(Except Greifer) Subjects had to reproduce the grip patterns displayed. In total, they had to switch amongst 5 grip patterns.
Task 2	Subjects had to build a castle made up of 6 blocks.
Task 2b	At the end of Task 2, subjects had to drop the smallest cube positioned on the top of the castle. To execute this action with the i-Limb and the Bebionic, it was required to change the mode to obtain the pointing index position.

Table 5.2: Task reminder

5.2.1 Greifer

As explained before, Greifer was the first prosthesis tested for all the subjects.

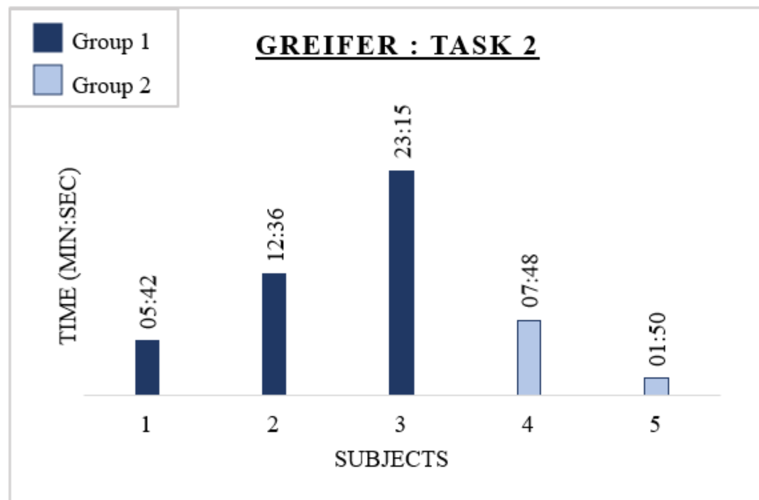


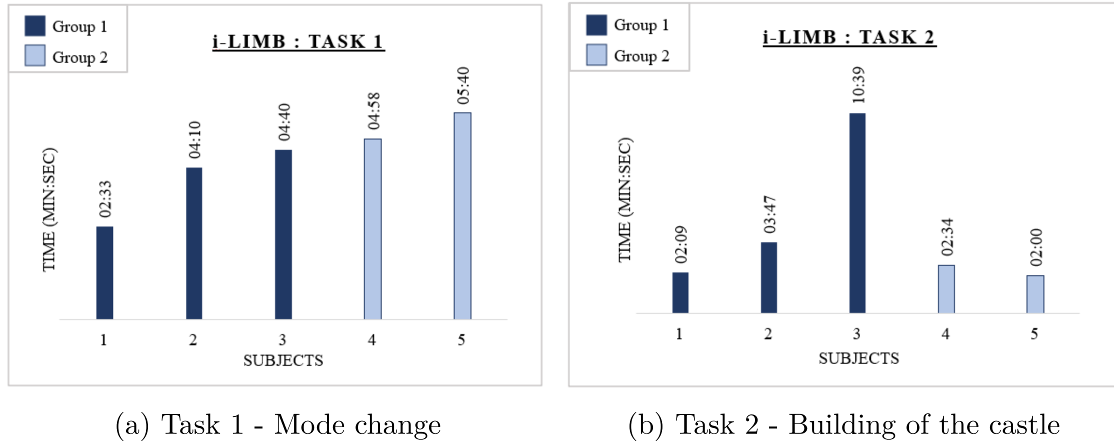
Figure 5.1: Time completed by the subjects to build the castle with the Greifer prosthesis.

The average times needed by the subjects to perform the task are displayed in **Table 5.3**.

Task \Group	1	2	1 & 2
Task 2	13’51"	4’49"	10’14"

Table 5.3: Average time for Task 2 with Greifer.

5.2.2 i-Limb



(a) Task 1 - Mode change (b) Task 2 - Building of the castle

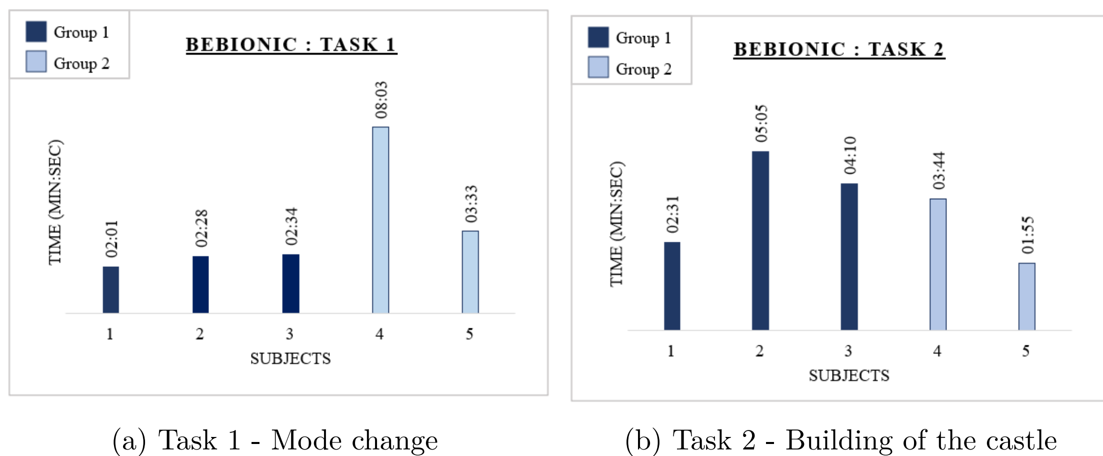
Figure 5.2: Time taken by the subjects to perform the two tasks with the i-Limb prosthesis. Group 1 (resp. Group 2) includes subjects having tested the i-Limb in second position (resp. third position).

The average times needed by the subjects to perform the tasks are displayed in **Table 5.4**.

Task \Group	1	2	1 & 2
Task 1	3’48"	5’19"	4’24"
Task 2	5’32"	2’17"	4’14"

Table 5.4: Average time for Task 1 and 2 with i-Limb.

5.2.3 Bebionic



(a) Task 1 - Mode change (b) Task 2 - Building of the castle

Figure 5.3: Time taken by the subjects to perform the two tasks with the Bebionic prosthesis. Group 1 (resp. Group 2) includes subjects having tested the Bebionic in third position (resp. second position).

The average times needed by the subjects to perform the tasks are displayed in **Table 5.5**.

Task \Group	1	2	1 & 2
Task 1	2'21"	5'48"	3'44"
Task 2	3'55"	2'50"	3'29"

Table 5.5: Average time for Task 1 and 2 with Bebionic.

5.2.4 General overview

All the results of the 3 prostheses for Task 1 and Task 2 are summed up in **Table 5.6**.

Task	Group	Greifer	Bebionic		i-Limb	
Task 1	1	/	2'21"	3'44"	3'48"	4'24"
	2		5'48"		5'19"	
Task 2 (block castle)	1	10'14"	3'55"	3'29"	5'32"	4'14"
	2		2'50"		2'17"	

Table 5.6: Overview of the average times for each group, task and prosthesis. Group 1 have tested i-Limb prosthesis in second place and Bebionic in third place while Group 2 have tested Bebionic in second place and i-Limb in third place. Results associated to the prostheses tested in second place (resp. third place) are highlighted in green (resp. yellow).

The time needed by each subject to perform Task 2b can be observed in **Table 5.7**.

Group	Subject	Greifer	Bebionic	i-Limb
1	1	/	17"	31"
	2	30"	/	/
	3	/	1'04"	/
2	4	/	11"	2'10"
	5	/	30"	36"

Table 5.7: Overview of the results obtained by each subject to perform Task 2b. Results associated to the prostheses tested in second place (resp. third place) are highlighted in green (resp. yellow). Unavailable results are marked by "/".

5.3 Survey results

The questionnaire given to the subjects can be found in **Appendix H.1**. In the following tables, the terms "before" and "after" indicate the survey it revers to, if it is the one completed before or after the VR immersion.

5.3.1 General criteria (from Q3 to Q14)

The subjects were first asked to classify the 3 prostheses for each criterion proposed (**Table 5.8**).

Criteria	Before	After
Aestheticism	+ i-Limb - Greifer	+ i-Limb / Bebionic - Greifer
Functionality	+ Bebionic - Greifer	+ i-Limb - Greifer
Robustness	+ Greifer - i-Limb	+ Greifer - Bebionic
Intuitiveness	+ Greifer - Bebionic / i-Limb	+ Greifer - Bebionic
Innovation	+ Bebionic / i-Limb - Greifer	+ Bebionic / i-Limb - Greifer
Motivation	+ Bebionic - Greifer	+ i-Limb - Greifer

Table 5.8: Results of the survey (from Q3 to Q14) before and after that the subjects have been immersed in VR. The sign "+" indicates the prosthesis the most voted for the first position, and the sign "-", the prosthesis the most voted for the last position.

5.3.2 Daily activities (from Q15 to Q17)

For each prosthesis, the subjects were asked to check all the activities they would be comfortable to perform with the given prosthesis. Eight activities were proposed: eat, dress, use a phone, shop, cook, clean and maintain a house, do the laundry and travel (by car, bike, etc).

The **Table 5.9** compares the results obtained before and after being immersed in VR for each prosthesis. By instance, from the survey made before the VR immersion, 20% of the subjects think they would be comfortable to dress with the Greifer as a prosthesis. Not all the results are shown, the full table with the results of each activity can be found in **Appendix H.2**.

	Greifer		i-Limb		Bebionic	
Activity	Before	After	Before	After	Before	After
Dress	20 %	60%	60 %	100 %	100 %	100 %
Cook	60 %	40 %	100 %	100 %	100 %	100 %
Travel (car, bike, ...)	40 %	60%	60 %	100%	80 %	80 %
Clean and maintain a house	100 %	80%	80 %	100 %	100 %	80 %
Average	55 %	60%	75 %	100 %	95 %	90 %

Table 5.9: For each prosthesis, percentage of the subjects that would be comfortable to do a given activity with this prosthesis (from Q15 to Q17).

Results obtained for the activities "Eat" and "Use a phone" are shown in order to highlight the difference between the percentages (**Table 5.10**).

Activity \Prosthesis	Greifer	i-Limb	Bebionic
Eat	40 %	100 %	100 %
Use a phone	20 %	80%	80 %

Table 5.10: For each prosthesis, percentage of the subjects that would be comfortable to do a specific activity with this prosthesis. Results from the survey made after the immersion in VR.

5.3.3 Final Choice (Q18 and Q19)

At the end, the subjects had to choose which prosthesis they thought was the most adapted for them (Q18), see **Table 5.11**.

	Greifer	i-Limb	Bebionic
Subjects			
Before	/	1, 4	2, 3, 5
After	/	1, 2, 4, 5	3
Percentage of the subjects			
Before	0 %	40 %	60 %
After	0 %	80 %	20 %

Table 5.11: Individual final choice of the subjects and total percentages of the subjects having chosen the prosthesis, after and before having tested the VR (Q18).

The final question of the second survey (Q19) was to point out the utility of the immersion in VR (**Table 5.12**).

Question	Yes	No
Did the training in virtual reality have an impact on your final choice of prosthesis ?	100%	0%

Table 5.12: Utility of the VR session (Q19).

5.3.4 General comments

To conclude, each subject was free to give a general remark:

- Subject 1: First the subject chose the i-Limb because it seemed more simple. The VR session allowed her to confirm her choice. According to her, the i-Limb was simpler than the Bebionic while having still a lot of modes.
- Subject 2: Nothing special.
- Subject 3: This is the only subject who preferred the Bebionic prosthesis after having tested it. It was really difficult for her to control the jump of the index

with the i-Limb model. It was more intuitive for her to have real commands such as the button and the movement of opposition of the thumb implemented for the Bebionic. About the Greifer, it was not enough precise according to her. In conclusion, she was able to discover, through the VR session, the difficulties and the advantages of each prosthesis.

- Subject 4: The real challenge for him was to perform the double signal used in the Bebionic. This is why he preferred the i-Limb. It was easier for him to switch between the modes.

- Subject 5: With the theoretical explanations, the subject did not clearly see the utility of the proximity chip. But after being able to test it in the virtual environment, he was more able to see the advantages of the chip. His first intuition led him to choose the Bebionic but at the end of the exercise, he was convinced by the i-Limb. He realised that having 8 modes available, such as the Bebionic, was maybe not essential to live. Nevertheless, he claimed that, as a music player, if a more complicated prosthesis could offer him the possibility to recover playing abilities, he would be ready to spend the time needed.

Chapter 6

Discussion

The discussion first interprets the results of the tasks and of the survey obtained in the previous chapter. Afterwards, limitations and further improvements are discussed.

6.1 Results Analysis

6.1.1 Task results analysis

Task 1 required more complex signals with the i-Limb than with the Bebionic.

Task 1 for both prostheses consisted in switching among 5 grip patterns. The main difficulty observed, with the Bebionic, was the double opening signal to change the mode. Whereas with the i-Limb, it was the long opening signal (triggering the jump of the index). Nevertheless, with the Bebionic, the double signal was required only one time during this first task. We made the choice to ask to the subject to change only once the grip pattern inside a same group otherwise the task would have taken too much time and energy. However, with the i-Limb, 4 long opening signals were needed during Task 1. The assumption can be made that this is why Task 1 took longer in average with the i-Limb (4'24") than with the Bebionic (3'44").

Average time taken to perform Task 2 with the Greifer is higher than the ones needed with i-Limb and Bebionic.

As we can observe in **Table 5.6**, the average time needed by the subjects to perform the second task with the Greifer (10'14") is higher than the ones needed with the i-Limb (4'14") or with the Bebionic (3'29"). This can be easily explained by the fact that Greifer was the first prosthesis tested by the subjects. They had to discover how to use properly the opening/closing system activated thanks to their muscles.

With a small sample of subjects, the impact of each individual result is big.

In **Figure 5.1**, the time taken by subject 3 (23'15") is responsible for the high average time needed to perform Task 2 with the Greifer. If only subjects 1, 2, 4 and 5 are considered, the average time amounts to 6'59", which is still higher than the ones of i-Limb (4'14") and Bebionic (3'29"). This is the major inconvenient of having a small sample of subjects, the individual impact of each subject is high.

Some subjects understood better and used the opening/closing system with more ease than others.

It has to be taken into account that the system was more intuitive for some subjects than for others. For instance, subject 3 was often confused between the opening and the closing of the prosthesis. Which explained why she took more time to perform Task 2 with the Greifer (23'15") and i-Limb (10'39").

For some results, the reason of a high time was because the thresholds were not well adjusted or because of a wrong electrodes placement.

Subject 4, for example, was confronted with problems of threshold adjustment. Because the subject moved a lot during the task, and as the wires were limited, it caused the movement of the electrodes. So a new adjustment of the thresholds was needed. It took him 8 minutes to perform Task 1 with the Bebionic (**Figure 5.3a**) because it was really hard for him to perform the double opening signal with non adapted thresholds.

The test order did not have a major influence on the results obtained to perform Task 2 with the i-Limb or the Bebionic.

Separating subjects into two groups aimed to see the impact of the prostheses test order, especially between the Bebionic and the i-Limb. It is hard to draw conclusions with such a small sample of subjects. However, by examining the graphs related to Task 2 (see graphs in **Figure 5.2b** and in **Figure 5.3b**), a trend can be observed for some subjects. Indeed, subjects 3 and 4 took both less time the third time than the second time to build the castle. As an example, subject 3 took in the second place 10'39" with the i-Limb and then 4'10" in the third place with the Bebionic, whereas the commands were exactly the same (no grip change was asked).
Nevertheless, this trend is not observed with the 3 other subjects. The results of subjects 1 and 5 are pretty similar between their second and third test. On the contrary, subject 2 took less time with the i-Limb (3'47") than with the Bebionic (5'05"), whereas the i-Limb was her last prosthesis. To sum up, based on these observations, we can not conclude that test order had a major influence on the results obtained to perform the second task.

The test order did not impact the final choice of the subjects.

One might have feared that test order would influence the final choice of the subjects because by testing more, the subjects could be more comfortable with the last prosthesis tested. Nevertheless, regarding the results of the 5 subjects, such a trend is not observed. Subjects 1 and 2 selected the i-Limb (**Table 5.12**) even though their last prosthesis was the Bebionic.

Bebionic and i-Limb prostheses were virtually more precise to execute Task 2b compared to the Greifer.

Time results for Task 2b are presented in **Table 5.7**. Most of them are unavailable because the castle collapsed when subjects were trying to execute the task. In order

to avoid tiring the subjects by asking them to rebuild the castle, task was stopped. It can be observed that 4 times out of 5, subjects were not able to drop the smallest cube with the Greifer. The clamp was indeed less precise that the pointing index finger of the two other bionic hands.

6.1.2 Survey results analysis

After the VR session, i-Limb was considered as the most functional prosthesis. Greifer for both surveys was said to be the most robust device.

Table 5.8 shows that subjects did not significantly change their opinion about the prostheses in regards to the proposed criteria, except some i-Limb/ Bebionic inversions. For instance, after the VR session, most of the subjects voted the i-Limb as the most functional prosthesis whereas the Bebionic had the first place before. The Greifer remained the prosthesis the least beautiful, functional and innovative one voted by the subjects. But before and after the immersion, Greifer was considered as the most robust and intuitive prosthesis.

Subjects were more comfortable to use the i-Limb or the Bebionic for daily activities. After the VR session, i-Limb became the most voted prosthesis for the different activities.

Table 5.9 illustrates some opinion changes about practical tasks feasibility. Greifer remained less popular than the two other prostheses for the different activities. Though the Bebionic was considered as the the best one at the beginning (95% of the subjects were comfortable to execute the 4 activities proposed with the Bebionic), the i-Limb results finished with the highest increase. Indeed, first the average percentage was equal to 75%, and after the VR session, it increased up to 100%.
For more specific activities, such as eating or using a phone (**Table 5.10**), the percentages of the Greifer (20% and 40%) were really low compared to the ones obtained by the two other hands (80% or 100%).

First, most of the subjects preferred the Bebionic as a final choice, but after having tested virtually the prostheses, i-Limb was the favorite one.

Firstly, 60% of the subjects chose the Bebionic as their final prosthesis on the basis of the theoretical explanations. After the VR session, except one subject, all of them chose the i-Limb (**Table 5.11**). With the Bebionic, most of the subjects claimed to be confused about the 8 grips map and the 3 control inputs available. It required also to be constantly aware of which mode was activated. Indeed, with the Bebionic, to have access to a new mode it is necessary to know the current mode. The real advantage with the i-Limb is that it does not depend on the current mode. The same command is used each time to activate a same mode.

According to the subjects, having the opportunity to test virtually the prostheses was really helpful in the prosthesis selection process.

As shown in **Table 5.12**, 100% of the subjects claimed that virtual reality helped them to chose the final prosthesis, either for changing their choice (subjects 2 and

5), either for comforting them in their choice (subjects 1, 3 and 4). The reasons are multiple. First, it allowed them to fully understand the mechanism of each prosthesis. Without testing them, some control methods remained abstract, such as the jump of the index with the i-Limb. Subject 5 also explained that, thanks to VR session, he understood fully the potential of the proximity chip used with the i-Limb, a concept that was initially not clear for him.
Besides, subjects understood, thanks to the VR tasks, the trade-off between the number of grip patterns available and the complexity it implied. Indeed, before the VR immersion, subjects attached a lot of importance to the number of grip patterns available in a prosthesis. Some of them voted initially for the Bebionic for this reason. After the experiment, subjects realised that having an easy control was more important than having lots of different positions.

6.2 Limitations and Improvements

Once the prototype has been tested on the subjects, it appeared that this first version of our setup could be improved in many ways. This section first discusses about the limitations and further improvements of the prototype and the protocol. Then, the limitations directly linked to Unity Software are explained. Finally, a last point addresses the improvements required to adapt the setup to real ULA patients.

6.2.1 Prototype

Muscle computer interface

According to Ghazi et al. scoping review [46], there are numerous studies that have developed VR systems similar to the one we have developed. Only one study used the conventional dual EMG electrode channel [60], such as the one implemented in our prototype. The other studies used, for the muscle computer interface, an eight EMG electrodes channel as well as a pattern recognition controller [49, 61, 62, 63, 64]. Pattern recognition and multiple EMG electrodes may be the future for myoelectric prostheses (see Adam's Hand prosthesis in **Appendix E**), however, it is not the reality that ULA patients must face with their current myoelectric prosthesis.

In order to replicate commercially available myoelectric prostheses, conventional dual EMG electrode channel is then the more relevant tool to use. However, the one we have implemented can still be improved. First, our prototype works with wet electrodes whereas in real prostheses, dry electrodes are used. Secondly, electrodes are linked to the Arduino by 0.45m long wires. During the exercises, the subjects had to pay attention to not damage the equipment. Even if tasks did not require large movements, it limited the freedom of the right hand.
In short, further improvements should use wireless dry electrodes in order to better imitate real prosthesis interface.

Threshold adjustments

To adjust the thresholds, the subjects were normally already immersed in VR. Nevertheless, after having tested the two first subjects, we noticed that it was easier for them to proceed this step outside the VR. Indeed, at the beginning, subjects needed to see the real movements performed with their hand. Otherwise, without external assistance, the subjects were unconsciously trying random movements searching for the one activating the signal. It is better to avoid such a situation because it produces noisy rough signals due to the activation of unwanted muscles.

Besides, several subjects asked if it was possible to keep the panel with signals feedback during prosthesis test session (see **Figure 3.12**). Such a feedback is not present in a real prosthesis but it seems nevertheless a justified improvement for the test tool. Indeed, it could be interesting to keep the panel when the subjects are still unfamiliar with the EMG activation. Otherwise, they often confused hand movements, which led to involuntary movements of the prosthesis, increasing the confusion.

Prosthesis implementation

In order to limit the test duration and to facilitate the understanding of the control methods, some prosthesis controls have been simplified. As a consequence, presented prostheses did not replicate all the real functionalities. **Tables 6.1, 6.2 and 6.3** highlight in red the non implemented features.
For instance, one extra movement is available with the Greifer. It allows to flex manually the wrist thanks to a flexible joint. More extra options can be observed with the i-Limb (**Table 6.2**), they offer the possibilities to implement more grip patterns and to have access to the wrist control.

By making the choice to implement or not certain options, it could influence the difficulty to use the prosthesis and so the subjects' opinion. For instance, the double emg1 signal was implemented in the virtual Bebionic but not in the i-Limb prosthesis. Generally, subjects found it really tricky to use, and for some subjects it was the reason why they did not like the Bebionic. If this option had been included as well in the virtual model of the i-Limb, this would probably have influenced the final choice of certain subjects.

Movement initiation	Action
Remark: closing/opening speed is proportional to the signal intensity	
emg0 signal	Closing
emg1 signal	Opening
Rotate manually the wrist	Rotation of the wrist
Flex manually the wrist	Lateral flexion of the wrist

Table 6.1: Summary of all the actions available with the Greifer prosthesis. In red, the actions not implemented in the presented tool.

Movement initiation	Action
Remark: the closing/opening speed is proportional to the signal intensity	
emg0 signal	Closing
emg1 signal	Opening
Grip change initiation	**Action**
Remark: a grip change can occur only if the prosthesis is in its initial position meaning fully open.	
Maintained emg1 signal	Jump of the index then move of the prosthesis in one of the 4 directions (left-right-top-bottom)
Proximity grip chip	Passing the prosthesis above the grip chip
emg0 + emg1 signals	Co-contraction to have access to the wrist control
Double short emg1 signal	To have access to extra grip patterns
Triple short emg1 signal	To have access to extra grip patterns

Table 6.2: Summary of all the actions available with the i-Limb prosthesis. In red, the actions not implemented in the presented tool.

Movement initiation	Action
Remark: closing/opening speed is proportional to the signal intensity	
emg0	Closing
emg1	Opening
Grip change initiation	**Action**
Remark: a grip change can occur only if the prosthesis is in its initial position, mening fully opened.	
Double emg1 signal	Grip pattern change inside a same group
Top button pressed	Group change
Manual movement of the thumb	Group change: switching from opposition to lateral position of the thumb and vice versa
emg0 + emg1 signals	Switch to wrist control

Table 6.3: Summary of all the actions available with the Bebionic prosthesis. In red, the actions not implemented in the presented tool.

Longer test period should justify the implementation and the use of those additional functionalities. They require, on one hand, a better EMG control in order to master co-contraction, double and triple contraction. On the other hand, it requires a strong concentration from the subjects to keep in mind the control map, with all the control methods available. In the current prototype, these difficulties were already observed with the implemented features.

To conclude, it is probably not necessary that the virtual prostheses replicate exactly the real ones. Trade-offs must be made. The most important point is that the different levels of complexity are well understood in their globality.

Healthy hand implementation

The left valid hand was represented virtually by a frozen hand with a pointing finger. It was used just like a tool to interact with the prosthesis and the environment. Whereas this was partially intentional because the aim was to force the subjects to use their prosthesis, it did not correspond to a real healthy hand. The Vive controller used to control this left hand could be further exploited to offer more realistic functionalities. Different hand positions can be recognised by the joystick.

Another remark is that the valid hand was floating in the environment without being attached to a virtual forearm. This kind of details are important so that the patients have the real sensation to have a prosthesis.

Further applications

When looking at the VR environment developed in other studies from Ghazi et al. scoping review [46], Nissler et al. [49] created the most advanced virtual tool, providing both a proportional control of the opening and closing of the virtual hand, as well as 4 different hand movement patterns. Nevertheless, these features were not representative of any specific and commercially available myoelectric prosthesis. The purpose of their virtual tool was more about mastering an EMG controlled device, to help the ULA patients during the rehabilitation. As far as we known, our tool is one of the first virtual system that attempts to replicate commercially available myoelectric prostheses. With this in mind, it might be assumed that our tool may also be beneficial for rehabilitation.

6.2.2 Protocol

Sample Quality

An important limitation of this experiment was the sample size. Testing only five people was not enough to draw strong conclusions about the quality of the implemented tool. Moreover, the sample was not diverse, 3 subjects were students and none of the 5 was into a manual work or even handy. Yet, prosthesis selection strongly depends on the usual tasks of the patient. This could explain why none of the subjects chose the Greifer prosthesis, which is mainly designed for this type of tasks. In the testimony (**Appendix A**), the patient interviewed was handy and he claimed that the first prosthesis that drew his attention was the Greifer. In conclusion, further tests should be conducted on a more extensive sample, investigating the impact of the professions.

Intervention : training time

One of the main limitation of the protocol was the training time, meaning the time spent by the subjects to test virtually the prostheses. Each subject had on average

6 to 10 minutes with each prosthesis, and approximately 25 minutes in total[1] (see **Section 5.2.4**). If a short experimental period may be sufficient to highlight a significant effect of the VR tool on training outcomes, it may not be as relevant to select a prosthesis. Indeed, such a low amount of training time is probably not enough to fully understand and master the different prostheses.

Inspiration can be drawn from other similar studies that developed either virtual prosthesis simulators and/or serious games for upper limb prosthesis training and rehabilitation. As a point of reference, a literature review from Pérot and Chambon [20] explained that the whole process of prosthesis training and rehabilitation takes up to **2 months** from the pre-prosthetic phase to the final prosthesis fitting. Whereas our tool was not dedicated to rehabilitation, it appears clearly that a different approach will be needed in future iteration.

Terlaak et al. [65] experimented on their prosthesis simulator through **6 sessions of 2 minutes per day in 3 consecutive days**. This training period, while quite short as well, had the advantage to train the participant in using the virtual tool without creating any exhaustion. However, the purpose of their tool was mainly to train and not to help the ULA patient to choose its prosthesis, sessions of 2 minutes would be too short in our case.

Closer to this reality, Bouwsema et al. [66] conducted a **5 sessions** training experiment over the course of **2 weeks**, thus recreating what an ULA patient may go through during its rehabilitation process[2]. This last study may be a good option for a future experiment of our VR tool.
In summary, it is necessary to conduct a larger experiment on our VR system in terms of duration of the tests to allow participants to master each prosthesis before choosing the one they prefer.

Evaluation Method

Some improvements are also required about the way the subjects were evaluated. First, it concerns the videos of the manufacturers shown to the subjects during the theoretical presentation (see the protocol in **Section 4.4**). The aim of these videos was to give to the subjects a first sight of the use of each prosthesis. Nevertheless, the tasks presented in the videos could also limit the subjects' vision of the prostheses. For instance, during the i-Limb presentation video, there was a scene where a woman was shown while cooking. Obviously, it had a big impact when the subjects had to say if they would cook with the i-Limb. Subject 3 especially noticed the impact of those videos on its choice (**Section 5.3.4**). To be completely objective, the videos should show, in an equitable manner, the possible activities to perform with the

[1] This total time was obtained by adding all the average times of the test periods. Note that this time is representative of the time spent to test each prosthesis but not of the total time spent in VR. By taking into account the failed trials and other equipment readjustment, the time spent in VR can be approximated to nearly 1h.

[2] The time spent for one session was not specified but by looking at the list of tasks, it can be assumed that it was much longer than a few minutes.

prostheses.

Secondly, as seen in the protocol, a part of the evaluation consisted in timing the subjects when they were performing the 3 tasks. Task 2b was the less successful in terms of results (**Table 5.7**), indeed most of the time, the castle collapsed before the subjects could manage to drop the small cube. The purpose of this task was to involve the pattern change and the interaction with objects in a same exercise. A new version of Task 2b should be developed in the next version of the protocol, but this time with having the guarantee that each subject will be able to finish it. It is important to note that it is really tiring for the subjects to execute the tasks, so the duration and the number of tasks are important parameters to take into account.

6.2.3 Virtual reality: Unity Software

Some limitations are not firstly due to the setup, but to the existing virtual reality possibilities. The main limitation of using Unity, or any virtual reality software, is that the weight and inertia of the prosthesis can not be taken into account. However, these features are important in the selection of a prosthesis. As explained in **Appendix D**, weight is among one of the main challenge in the development of the current prostheses.

The other main difficulty concerns the incompatibly of the virtual and real constraints. Indeed, the subject could virtually go through the virtual table with the prosthesis, which was not physical. A solution to avoid this was to place a real table with the same position and dimension than the virtual table, so the subject was physically stopped. But the problem with this configuration was that the real table hindered the flexion of the subject required to activate the movement of the prostheses, indeed the hand hit the table. Nevertheless, this last point concerns only healthy subjects.

6.2.4 From healthy subjects to ULA patients

In the future, this prototype aims to be tested on ULA patients. In the current setup, it has been imposed that the prosthesis was attached to the right hand (this has been stated in **Section 3**). The first improvement would be to adapt the game for left hand amputee patients, so that the prototype is suitable for any patient.

Besides, it has to be noted that the study was conducted on healthy patients, with fully efficient muscles. When the subjects had to activate the signals, they could perform real movements. The task is much more difficult for ULA patients, as they have to imagine performing the movements to activate their remaining muscles. A relevant question to study is where, in the journey of the amputee patients, this program could be used. If the patients had already started the rehabilitation, they may be more able to control their muscle signals. Otherwise, if the setup is used before the rehabilitation, it is important to plan extra sessions so that the patients can learn to handle the opening/closing system.

Conclusion

The choice of prosthesis is a key step in the journey of an amputee. Without having the possibility to test the device, it is easy to imagine the difficulty that a patient has when choosing an adapted prosthesis. On the market, several models are proposed and the complexity level varies considerably from one model to another.
To talk about this problematic, we had the opportunity, during this semester, to meet an ULA patient, Mr D. (**Appendix A**). This experience allowed us to have a patient's real point of view. Mr D. testified that one of the most difficult steps for him was the choice of his prosthesis. At this point, the relevance of our work made a lot of sense.

The tool implemented, as part of this thesis, focused on the main control and geometry of 3 commercialized prostheses: the Greifer clamp and the Bebionic hand both developed by Ottobock, and the i-Limb Quantum prosthesis proposed by Ossür (**Section 3.4**). To simulate the muscle prosthesis interface, we have built a setup made up of 2 electrodes and one Arduino. A virtual environment was developed in Unity in order of offering the subjects the possibility of discovering the 3 prostheses through different tasks.
The scope review, realised in parallel with this thesis, confirmed that the tool proposed was pioneering in its field (**Section 2.4**).

Many features came into play during the development of the virtual prostheses; the number of grip patterns implemented, the delay to activate a given command, the chosen control when several are proposed, etc. Therefore, we had to make decisions, sometimes arbitrary, sometimes guided by the information given by the manufacturers. With this work, our first ambition was to highlight the relevant features of the prosthesis being implemented. The best way to answer this question would be to ask to an ULA patient wearing this prosthesis for a certain amount of time, to do a virtual test. That way, the patient would be able to evaluate the realism of our prototype. But in fact, the answer is not that simple as there are several control modes for a same prosthesis. Which makes the task even more difficult to know which features are relevant to implement.

Due to the sanitary crisis (Covid 19), our tests were conducted on only 5 healthy subjects. Therefore, the next version of this study should be conducted on a bigger and more extensive sample of subjects. Another improvement about the process would be to prolong the duration of the training time. For instance, by conducting a 5 sessions training experiment over the course of 2 weeks.

Although the sample was small, it enabled us to draw many relevant conclusions. All the subjects testified that the VR session allowed them to better understand the mechanism and the different challenges of each prosthesis. Before the immersion in VR, the explanations of the prosthesis controls remained abstract for them. Even if some subjects chose the same prosthesis twice (before and after the VR session), they explained that VR allowed them to consolidate their choice. Thanks to these feedback, it can be concluded that virtual reality is a successful tool to test and compare prostheses.

To sum up, by testing the prostheses virtually, the subjects realised the complexity of the control of a prosthesis. It is not intuitive. It is clear that the future generation of prostheses will develop system such as the Myo Plus System (**Section 2.3**) and the Adam's Hand (**Appendix E**). These advanced technologies work with 8 electrodes, instead of 2, and are much more intuitive. The user only has to activate the corresponding muscles by imagining a movement so that the prosthesis replicates this position. In the future, these technologies will probably be used for the majority of prostheses, simply because it works like a real arm. To be updated, our prototype should also be able to integrate such prostheses.

If the new generation of prostheses tends to be fully intuitive, will there still be a decisive stage in the choice of prostheses ? Yes probably, first because not everybody will be financially able to access the latest technology. Secondly, these new prostheses require many muscular signals. So if the residual limb is in bad condition, it is not always possible to have access to a large number of signals. This way, prostheses using 2 electrodes, like the ones we have implemented, can still have a role to play in the market.

Bibliography

[1] BionIT Labs. Launch of adam's hand campaign on mamacrowd. https://www.youtube.com/watch?v=qL1tSwpxMQM&feature=emb_title, 2019. [Accessed: 10/10/2019].

[2] Cifu David X. and Lew Henry L. Braddom's rehabilitation care: A clinical handbook, chapter 9, rehabilitation and prosthetic restoration in upper limb amputation. pages 51–56, 2017.

[3] Amputee Coalition. Upper-limb amputations, new york. 2012. [Accessed: 11/15/2020].

[4] Douglas Harper. Online etymology dictionary. https://www.etymonline.com/word/bionics, 2001-2020. [Accessed: 18/03/2020].

[5] C.W. Behets. Membre supérieur. *LIEPR1028 Anatomie locomotrice, description par région, FSM*, 2016.

[6] Wincenty Kilarski. Chapter 2 - Functional morphology of the striated muscle. In Jerzy A. Zoladz, editor, *Muscle and Exercise Physiology*, pages 27 – 38. Academic Press, 2019.

[7] Plonsey Malmivuo, Jaakko Malmivuo, and Robert Plonsey. *Bioelectromagnetism: principles and applications of bioelectric and biomagnetic fields*. Oxford University Press, USA, 1995.

[8] EHS anatomy & Physiology. Somatic autonomic nervous system. https://sites.google.com/site/ehsanatomyphysiologyaa/chapter-10-nervous-system/general-funtions-of-the-nervous-system/somatic-autonomic-nervous-system, 2013. [Accessed: 20/03/2020].

[9] Oliver J. and Teach me Anatomy. Muscles of the upper limb. https://teachmeanatomy.info/upper-limb/muscles/posterior-forearm/, 2017. [Accessed: 20/03/2020].

[10] Pierre M Montavon, Katja Voss, and Sorrel J Langley-Hobbs. Feline orthopedic surgery and musculoskeletal disease. pages 221–235, 2009.

[11] Dr. Cohen. Standard of care. http://standardofcare.com/Wrist. [Accessed: 19/03/2020].

[12] J.L. Thonnard. Les mouvements du poignet. *LIEPR1028 Anatomie locomotrice, Analyse du mouvement, FSM*, 2016.

[13] Marco Santello, Gabriel Baud-Bovy, and Henrik Jörntell. Neural bases of hand synergies. *Frontiers in computational neuroscience*, 7:23, 2013.

[14] Giovanni A Zappatore, Giulio Reina, and Arcangelo Messina. Analysis of a highly underactuated robotic hand. *Int. J. Mech. Control*, 18(2):17–24, 2017.

[15] Sylvestro Micera. Motor control of reaching and grasping. *BIOENG-486 Sensorimotor neuroprosthetics, EPFL*, 2019.

[16] Marc D Binder, Nobutaka Hirokawa, and Uwe Windhorst. Encyclopedia of neuroscience. 2009.

[17] K. Ziegler-Graham, E. J. MacKenzie, P. L. Ephraim, T. G. Travison, and R. Brookmeyer. Estimating the prevalence of limb loss in the united states: 2005 to 2050. *Arch Phys Med Rehabil*, 89(3):422–9, 2008.

[18] Partenamut. Prothèses bioniques : du hightec pour les bras et les jambes. `https://www.partenamut.be/fr/blog-sante-et-bien-etre/articles/protheses-bioniques`, 2019. [Accessed: 22/03/2020].

[19] Engineering National Academies of Sciences and Medicine. The promise of assistive technology to enhance activity and work participation, chapter 4. pages 99–141, 2007.

[20] C. Pérot and J.-P. Chambon. EMC - techniques chirurgicales - chirurgie vasculaire. Amputations des membres supérieurs. Volume 28, Issue 4, 2012.

[21] Empowering Human Potential Hanger Clinic. Stages of amputation and rehabilitation. `http://www.hangerclinic.com/new-patient/ampower/Documents/Stages_of_Amputation_and_Rehabilitation.pdf`. [Accessed: 01/04/2020].

[22] Aalborg University. Virtual reality eases phantom limb pain. `www.sciencedaily.com/releases/2017/05/170531102921.htm`, 2017. [Accessed: 29 March 2020].

[23] Herta Flor. Phantom-limb pain: characteristics, causes, and treatment. *The Lancet Neurology*, 1(3):182–189, 2002.

[24] Charles Faure, Annabelle Limballe, and Hugo Kerhervé. Fooling the brain, fooling the pain: The role of mirror therapy and modern uses in virtual reality. *Frontiers for Young Minds*, 7, 2019.

[25] John H. Bovvker, Robert D. Keagy, and Pradip D. Poonekar. *Atlas of Limb Prosthetics: Surgical, Prosthetic, and Rehabilitation Principles*, chapter 25, Musculoskeletal Complications in Amputees: Their Prevention and Management. 1992.

[26] The serious injury law practice Serious Law. Effects of amputation. `http://www.seriousinjurylaw.co.uk/other-serious-claims/amputation/effects-of-amputation/`. [Accessed: 29/03/2020].

[27] Mayo Clinic. Residual limb pain. https://www.mayoclinic.org/diseases-conditions/residual-limb-pain/cdc-20447167. [Accessed: 29/03/2020].

[28] Christina Rock Gambrell. Overuse syndrome and the unilateral upper limb amputee: consequences and prevention. *JPO: Journal of Prosthetics and Orthotics*, 20(3):126–132, 2008.

[29] Arm Dynamics. Prosthetic options. https://www.armdynamics.com/our-care/prosthetic-options. [Accessed: 13/11/2019].

[30] Bebionic. Everyday life with the Bebionic, hand therapy and rehabilitation. https://shop.ottobock.us/media/pdf/BebionicTherapyBrochure2018.pdf, 2018. [Accessed: 01/04/2020].

[31] Federico Gaetani, Patrizio Primiceri, Giovanni Antonio Zappatore, and Paolo Visconti. Hardware design and software development of a motion control and driving system for transradial prosthesis based on a wireless myoelectric armband. *IET Science, Measurement & Technology*, 13(3):354–362, 2018.

[32] Ottobock. Axon hook in action. https://www.youtube.com/watch?v=jXoW6RCWsh8. [Accessed: 09/04/2020].

[33] Manfredo Atzori and Henning Müller. Control capabilities of myoelectric robotic prostheses by hand amputees: a scientific research and market overview. *Frontiers in systems neuroscience*, 9:162, 2015.

[34] Ottobock. Myoelectric prosthetics. https://www.ottobockus.com/prosthetics/upper-limb-prosthetics/solution-overview/myoelectric-prosthetics/. [Accessed: 10/04/2020].

[35] Ottobock. System electric greifer: Firm hand with an easy touch. https://www.ottobockus.com/prosthetics/upper-limb-prosthetics/solution-overview/system-electric-greifer/. [Accessed: 09/04/2020].

[36] Ottobock. Bebionic hand, the world's most lifelike bionic hand. https://www.ottobockus.com/prosthetics/upper-limb-prosthetics/solution-overview/bebionic-hand/. [Accessed: 10/10/2019].

[37] Partners in Prosthetics Covvi. Grip patterns. https://www.covvi.com/covvi-hand/grip-patterns/. [Accessed: 23/01/2020].

[38] Touch Bionic. Touch bionic solutions. https://touchbionics.com/. [Accessed: 12/11/2019].

[39] Touch Bionic. Formation interactive pour l'utilisation d'i-limb hand. http://training.touchbionics.com/quantum-fr.html. [Accessed: 12/11/2019].

[40] Ossur. Instructions for use, I-Limb wrist. https://assets.ossur.com/library/41187/i-Limb%20Quantum%20Notice%20d'utilisation%20-%20i-Limb%20Wrist.pdf, 2019. [Accessed: 09/04/2020].

[41] Ottobock. Myo plus - the next generation of prosthetic control. https://www.youtube.com/watch?v=B8Z_2tMUeiw, 2018. [Accessed: 06/04/2020].

[42] Ottobock. Myo plus pattern recognition in practice. https://shop.ottobock.us/media/pdf/2945709MyoPlusTherapyandTrainingBrochure.pdf, 2020. [Accessed: 06/04/2020].

[43] Katherine A. Raichle, Marisol A. Hanley, Ivan Molton, Nancy J. Kadel, Kellye Campbell, Emily Phelps, Dawn Ehde, and Douglas G. Smith. Prosthesis use in persons with lower- and upper-limb amputation. *Journal of rehabilitation research and development*, 45(7):961–972, 2008.

[44] E. A. Biddiss and T. T. Chau. Upper limb prosthesis use and abandonment: a survey of the last 25 years. *Prosthet Orthot Int*, 31(3):236–57, 2007.

[45] Fahimi F. Dawson MR, Carey JP. Myoelectric training systems. 2011.

[46] H. Ghazi, A. Lheureux, and R. Ronsse. Virtual rehabilitation and upper limb prosthesis: A systematic scoping review. *Faculté des sciences de la motricité, Université catholique de Louvain.*, 2020.

[47] G. Tieri, G. Morone, S. Paolucci, and M. Iosa. Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies. *Expert Rev Med Devices*, 15(2):107–117, 2018.

[48] M. V. Sanchez-Vives and M. Slater. From presence to consciousness through virtual reality. *Nat Rev Neurosci*, 6(4):332–9, 2005.

[49] C. Nissler, M. Nowak, M. Connan, S. Buttner, J. Vogel, I. Kossyk, Z. C. Marton, and C. Castellini. Vita-an everyday virtual reality setup for prosthetics and upper-limb rehabilitation. *J Neural Eng*, 16(2), 2019.

[50] Arduino. Arduino official store. https://store.arduino.cc/, 2020. [Accessed: 28/05/2020].

[51] HTC corporation. Vive. https://www.vive.com/, 2011-2020. [Accessed: 30/05/2020].

[52] Advancer Technologies. Myoware muscle sensor. https://cdn.sparkfun.com/assets/learn_tutorials/4/9/1/datasheet.pdf, 2015. [Accessed: 20/02/2020].

[53] NEUROSPEC AG Webshop. Mini adhesive electrodes (covidien). https://shop.neurospec.com/mini-adhesive-electrodes-covidien. [Accessed: 12/06/2019].

[54] Todd R. Farrell and Richard F. Weir. The optimal controller delay for myoelectric prostheses. *ieee transactions on neural systems and rehabilitation engineering*, Vol 15, 2007.

[55] Wikipedia. Unity (moteur de jeu). `https://fr.wikipedia.org/wiki/Unity_(moteur_de_jeu)`, 2020. [Accessed: 28/05/2020].

[56] Ossur. I-limb quantum. `https://www.ossur.fr/solutions-protheses/sp-produits/touch-solutions/i-limb-ultra`, 2019. [Accessed: 11/04/2020].

[57] Jan P. Vandenbroucke, Erik von Elm, Douglas G. Altman, Peter C. Gøtzsche, Cynthia D. Mulrow, Stuart J. Pocock, Charles Poole, James J. Schlesselman, Matthias Egger, and Strobe Initiative for the. Strengthening the reporting of observational studies in epidemiology (strobe): Explanation and elaboration. *PLOS Medicine*, 4(10):e297, 2007.

[58] Erik von Elm, Douglas G. Altman, Matthias Egger, Stuart J. Pocock, Peter C. Gøtzsche, Jan P. Vandenbroucke, and for the STROBE Initiative. The strengthening the reporting of observational studies in epidemiology (strobe) statement: Guidelines for reporting observational studies. 18(6):800–804, 2007.

[59] Hermie J. Hermens, Commission des Communautés européennes, Biomedical, and Health Research Programme. *SENIAM : European recommendations for surface electromyography : results of the SENIAM project*. Roessingh Research and Development, [Pays-Bas], 1999.

[60] Hannes Kaufmann. Ottobock creates virtual reality training for upper limb amputees. *O&P Business News*, 21(12):70–70, 2012.

[61] I. Phelan, M. Arden, C. Garcia, and C. Roast. Exploring virtual reality and prosthetic training. pages 353–354, 2015.

[62] D. Dhawan, M. Barlow, and E. Lakshika. Prosthetic rehabilitation training in virtual reality. 2019.

[63] K. Odette and Q. Fu. A physics-based virtual reality environment to quantify functional performance of upper-limb prostheses. *Conf Proc IEEE Eng Med Biol Soc*, 2019:3807–3810, 2019.

[64] Eccles Health Sciences Library Digital Publishing. Virtualimb: Box & block test. 2017.

[65] B. Terlaak, H. Bouwsema, C. K. van der Sluis, and R. M. Bongers. Virtual training of the myosignal. *PLoS One*, 10(9):e0137161, 2015.

[66] H. Bouwsema, C. K. van der Sluis, and R. M. Bongers. Effect of feedback during virtual training of grip force control with a myoelectric prosthesis. *PLoS One*, 9(5):e98301, 2014.

[67] Jorge Ambrósio. Basic concepts in human motion. *BM - Biomechanics of Human Motion, Técnico Lisboa*, 2019.

[68] Alberto Esquenazi and Robert DiGiacomo. Rehabilitation after amputation. *Journal of the American Podiatric Medical Association*, 91:13–22, 02 2001.

[69] Benjamin Stephens-Fripp, Gursel Alici, and Rahim Mutlu. A review of non-invasive sensory feedback methods for transradial prosthetic hands. *IEEE Access*, 6:6878–6899, 2018.

[70] BionIT Labs. Press kit. `https://www.adamshand.it/presskit_eng.html`. [Accessed: 06/11/2019].

[71] Federico Gaetani, Giovanni Antonio Zappatore, Paolo Visconti, and Patrizio Primiceri. Design of an arduino-based platform interfaced by bluetooth low energy with myo armband for controlling an under-actuated transradial prosthesis. 2018.

[72] Karen Tatarian, Micael S Couceiro, Eduardo P Ribeiro, and Diego R Faria. Stepping-stones to transhumanism: An emg-controlled low-cost prosthetic hand for academia. In *2018 International Conference on Intelligent Systems (IS)*, pages 807–812. IEEE, 2018.

Appendix A

Testimony of an ULA Patient

On 6th Match 2020, we had the opportunity to meet Mr D. at the Hospital of Saint-Luc in Brussel. Mr D. is in his 40s and is a primary school teacher. In addition to this work, he regularly does capping work. While capping on a construction site, he felt from a ladder to a circular saw, cutting his forearm. On arrival at the hospital, the surgeons were very clear, it was not possible to fix the arm. Mr D. remained very positive. He claimed that he quickly accepted the loss of his arm. Faced with a year of recovery, he thought about many projects he would be able to carry out during this period. According to him, remaining active was the key to avoiding depression. Only three days after the accident, carefully packing his stump, he resumed his work of capping.

His health insurance totally covered the cost of some prostheses "packages". It has to be noted that Mr D. had absolutely no idea about the price of the different prostheses.
According to Mr D., the choice of the prosthesis was the most difficult step. He did not know which criteria to use and was unable to say directly which prosthesis was the most suitable for him. Moreover, Mr D. could not ask all his questions because the prosthesist did not speak the same language. He chose the prosthesis developed by Ottobock because the package included 4 interchangeable tools: the Bebionic hand, the Greifer clamp, a simple hook and a simple ring. That way he could postpone the choice of one more adapted prosthesis. During the meeting, Mr D. explained that, at the moment, he preferred the Greifer Hook because it seemed more robust whereas the Bebionic hand was too complex.

At the time of the interview, it was 3 months since Mr D.' amputation and he had received the Bebionic hand 3 days before. The training with the myoelectric prosthesis was conducted by the manufacturer. In the case of Ottobock, it began with 3 successive computer games. The first consisted of independently increasing the tension above a certain threshold of both electrodes. A graph of the tension over time was displayed on the computer (one graph by electrode).
The second game represented the bionic hand on a screen. A contraction on the first electrode (resp. second electrode) closed (resp. opened) the hand. Mr D. especially liked this game because he could see a practical application. This greatly increased

his motivation.
The third and last game aimed to teach the user how to manage the duration of a contraction. It consisted of driving two cars (one by electrode) and avoiding obstacles. The direction of the car was controlled by the contraction duration.
It was recommended to train 50 minutes per day. However, in order to obtain good results, Mr D. spent several hours training each day. Thanks to his great motivation, after only two weeks he had completed all the games.

Figure A.1: Mr D. trying to grasp a soft bottle at the beginning of being trained to use the prosthesis.

An important remark concerned the issue of weight of the prosthesis. According to Dr. J-M Vanmarsenille, the doctor in charge of Mr D., all upper-limb amputees complain about the heaviness of their prosthesis, even if it weighs less than a real arm. Mr D. also mentioned the feeling of an heavy prosthesis. When he had to choose whether he wanted to have a motorized wrist, he refused because it would add extra weight.

In conclusion, according to Mr D., the most difficult part was the choice of the prosthesis. On one hand because he was not able to specify what he really needed and on the other hand because he could not understand the advantages of the different prostheses.

Appendix B

Anatomical Movements

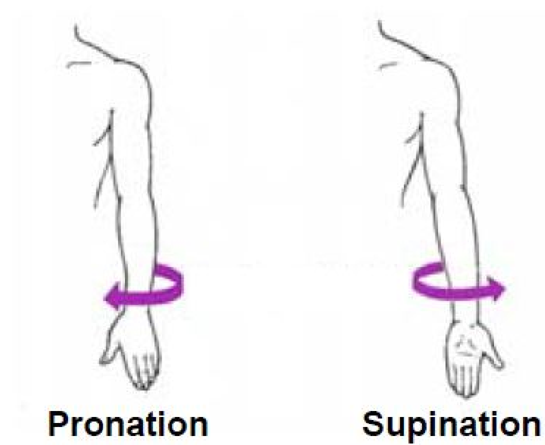


Figure B.1: Supination and pronation are specific terms used for rotational movements of the forearm in the outward and inward directions [67].

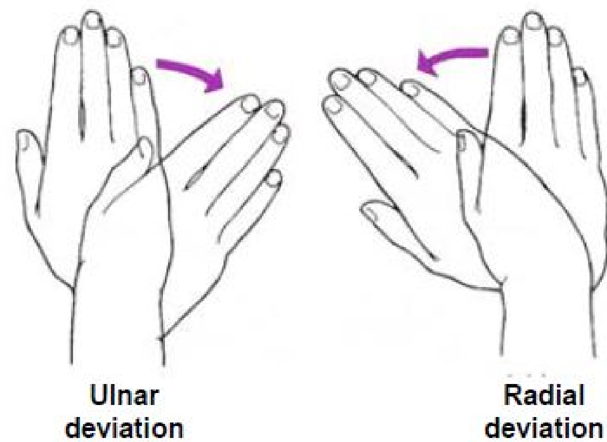


Figure B.2: **Ulnar deviation**: hand rotation toward the ulna (little finger side). **Radial deviation**: Rotation of the hand at the wrist in the frontal plane toward the radius (thumb side) [67].

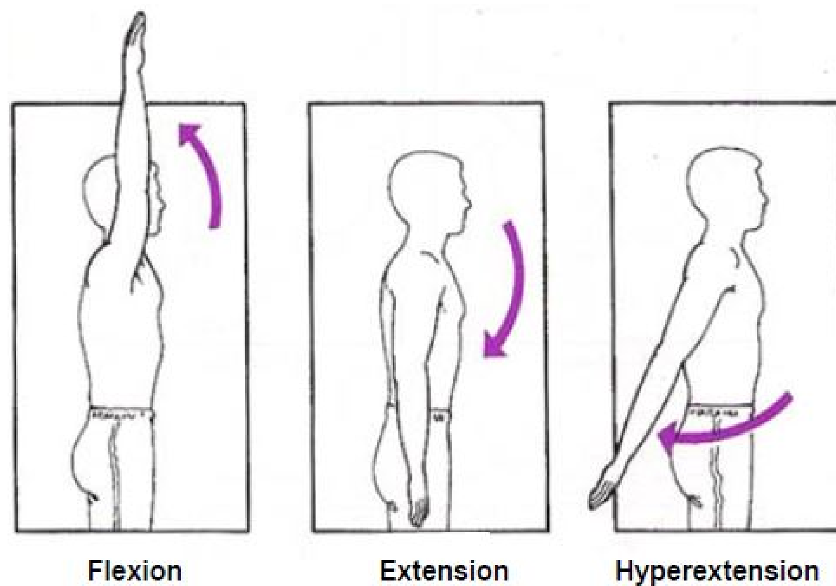


Figure B.3: Flexion, extension and hyperextension motions are in the sagittal plane of motion. **Extension**: is defined as the movement that returns a body segment to anatomical position from a position of flexion [67].

Appendix C

Traditional Amputee Rehabilitation and Prosthesis Training

Pre-prosthetic training and rehabilitation must start as soon as pain control and wound healing allows movement of the residual limb. The main objectives at this stage are to shape the residual limb, shrink the oedema, and increase muscle strength [68].

Once the wound is completely healed, training with the prosthesis can start. This section is based on a training program for prostheses developed by Ottobock [30]. First, care is needed to have a good posture during the exercise session. For successful prosthesis control, some recommendations are displayed in **Figure C.1**. Indeed, as it has been explained in **Section 1.2.3**, compensatory movements can lead, over time, to injury. Secondly, maximum concentration of the patient is required to ensure success.

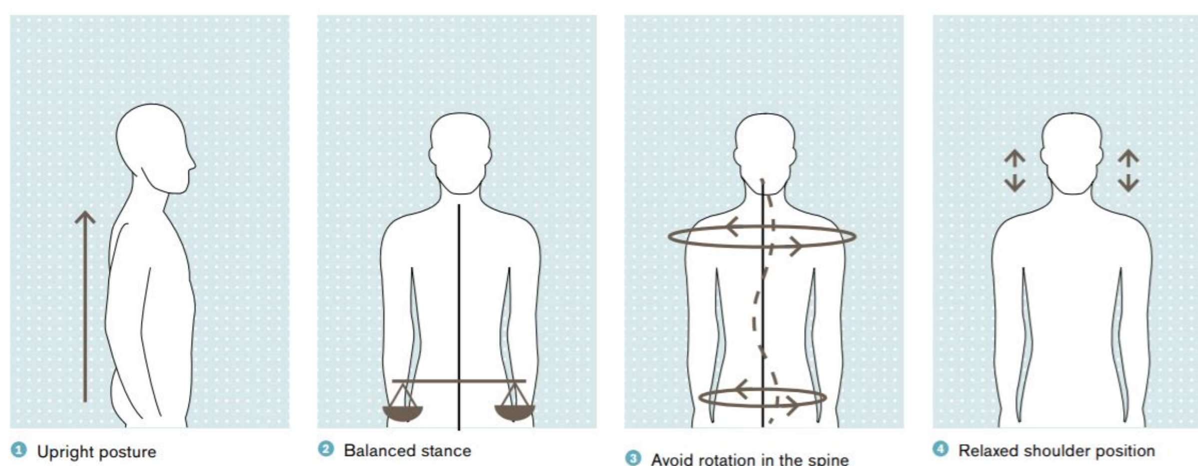


Figure C.1: Body posture recommended during training session [30].

C.1 Full Body Training

Losing a limb has a direct impact on the patient's balance. The goal of the following exercises (**Figure C.2**) is to restore balance and stability while increasing strength and endurance. Each exercise has to be executed for 10 or 15 seconds.

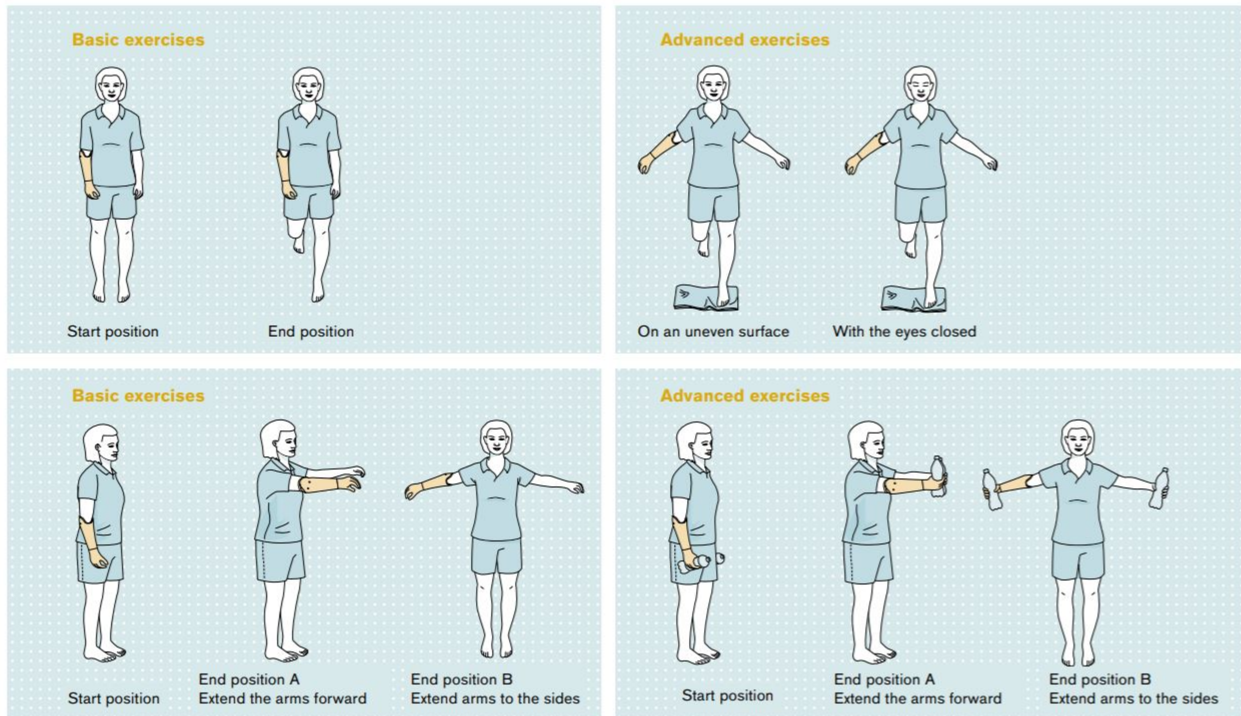


Figure C.2: Example of exercises: one-legged stance for balance and lifting the arms for shoulder and trunk strengthening [30].

C.2 Controls training: active and passive functions

Passive functions

The phase of learning how to control the prosthesis comes next. Functions clearly depends on the prosthesis. The general case of a myoelectric prosthesis is considered here. There are the **passive functions** such as:

- Program switch (main button displayed on the back of the hand) functions: for instance, turning the prosthesis on and off, or alternating between the primary and secondary grip patterns.
- Manual thumb adjustment
- Locking/unlocking the wrist
- Detaching the hand from/reattaching the hand to the prosthetic socket

- Charging the prosthesis

Active functions

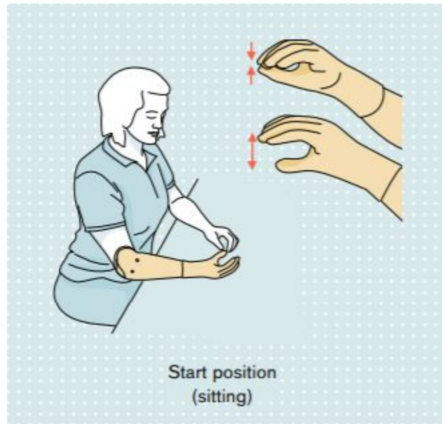


Figure C.3: Opening and closing the hand [30].

Afterwards **active functions** include opening and closing (via muscle myoelectric signals) and the rotation of the wrist. The first aim is to open and close the hand, in both lateral and opposition modes (**Figure C.3**). Secondly, the exercise is to test the wrist rotation, again in lateral and opposition. Then more advanced parameters can be explored by varying the speed or the degree of closure of the grip (full and partial grip closure/opening). The patient can also try without visual feedback.

Once he/she is confident, the next step is to combine hand and wrist movements. Note that the exercises can be performed, after a while, in a standing position, with the arm on its back or when the patient is walking.
Below two examples of active functions training sequences:

- Open the hand quickly ⇒ Close slowly ⇒ Open halfway ⇒ Open fully ⇒ Close fully
- Open the hand ⇒ Rotate the wrist inwards ⇒ Rotate the wrist outwards ⇒ Close the hand

C.3 Controls training: interaction with objects

Once the active functions are mastered, it is time to interact with objects. To start the training, **indirect grasping** is advised, meaning that the valid hand takes the object to pass it to the prosthesis. In this way, the actual hand can perceive the shape of the object. The object can be a block, bottle, soft ball, plastic cup, cards, etc. Then comes the **direct grasping**, the object is directly grasped by the prosthetic hand (**Figure C.4**). Each exercise can be repeated from 10 to 15 times.

C.4 Controls training: activities of daily living (ADL)

The final step of the training is to incorporate activities of daily living with the aim of promoting the independence of the patient. A few examples are shown in **Figure C.5** but other activities, such as holding a knife to eat, tying shoelaces or carrying a bag, can be part of the training.

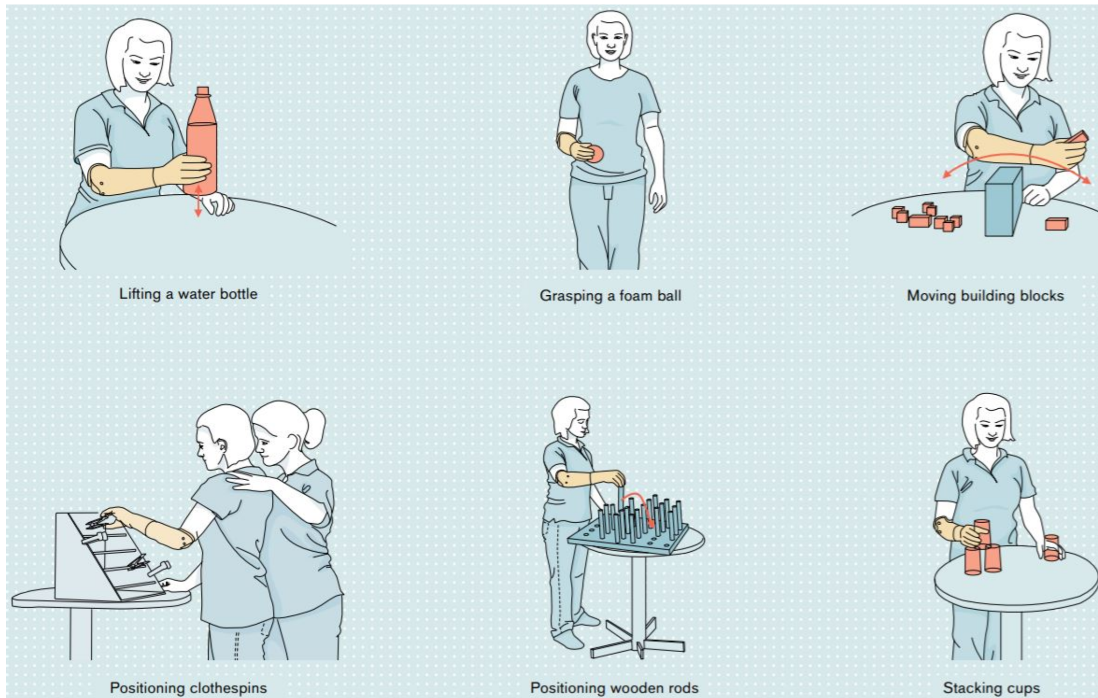


Figure C.4: Direct grasping of objects [30].

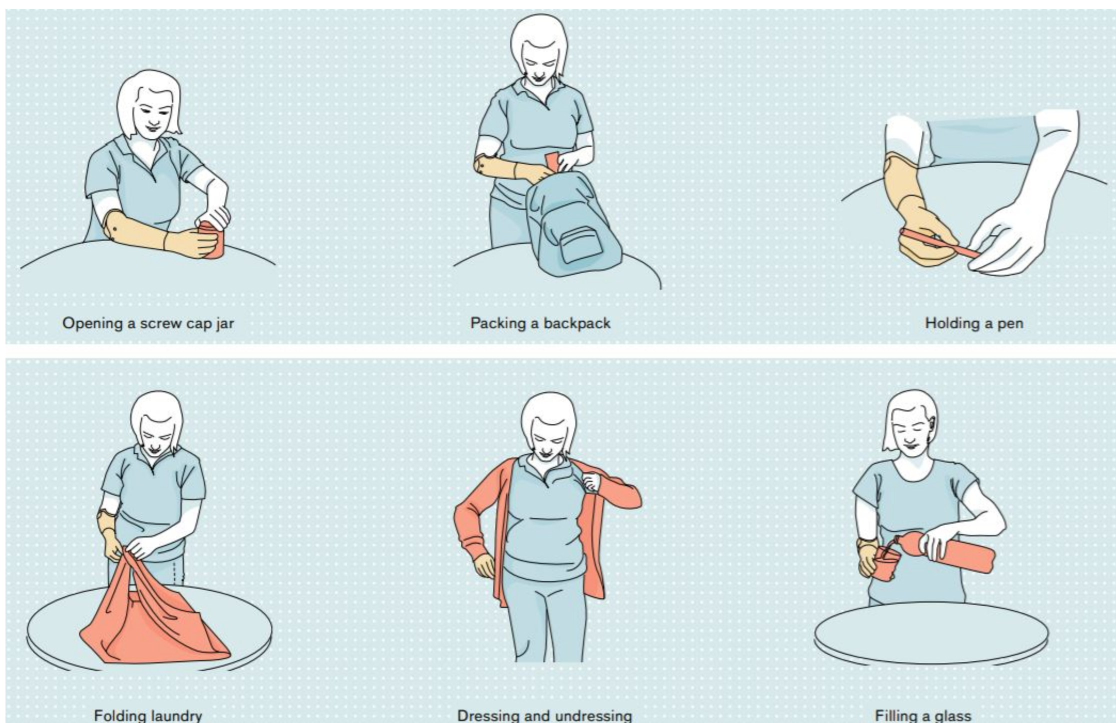


Figure C.5: Examples of activities of daily living [30].

Appendix D

Current Challenges with Bionic Prostheses

In this section, the current challenges of the bionic prostheses such as weight and the lack of sensory feedback are explained. Note that many other characteristics could also have been developed, such as the cost, which is extremely high if it is not covered by health insurance, or the battery life of the prostheses which generally only lasts a few hours.

D.1 Weight

Even if the prosthesis is generally lighter than an actual arm, the user often complains about how heavy the prosthesis. The higher the number of actuators, the more the prosthesis is heavy. In **Appendix A**, the interview with a severed patient, Mr D., is recounted. He testifies that when he had to choose whether or not to have the wrist motorized, he refused because of the extra weight it would have added. A current challenge is therefore to reduce the weight of the prostheses. A solution is to decrease the number of actuators while keeping the same number of DoFs of the prosthesis. This is the motivation behind the Adam's Hand prosthesis explained in **Appendix E**.

D.2 Sensory feedback

When a patient loses his/her hand, the brain, which governs sensorimotor control, no longer receives sensory feedback through the nerves of the hand. In other words, the closed-loop sensory feedback between the brain and the hand has been interrupted (**Figure D.1**). A good hand prosthesis needs to replicate the feelings of a real hand: intuitive control, light and compliant design, and sensory feedback. Nowadays, one of the main challenges faced by the prostheses is to restore sensory feedback. Such prostheses are called **bidirectional**.

The means of providing a feedback can be **invasive** or **non-invasive**. The level of invasiveness depends on how the device interacts with the body. Non-invasive

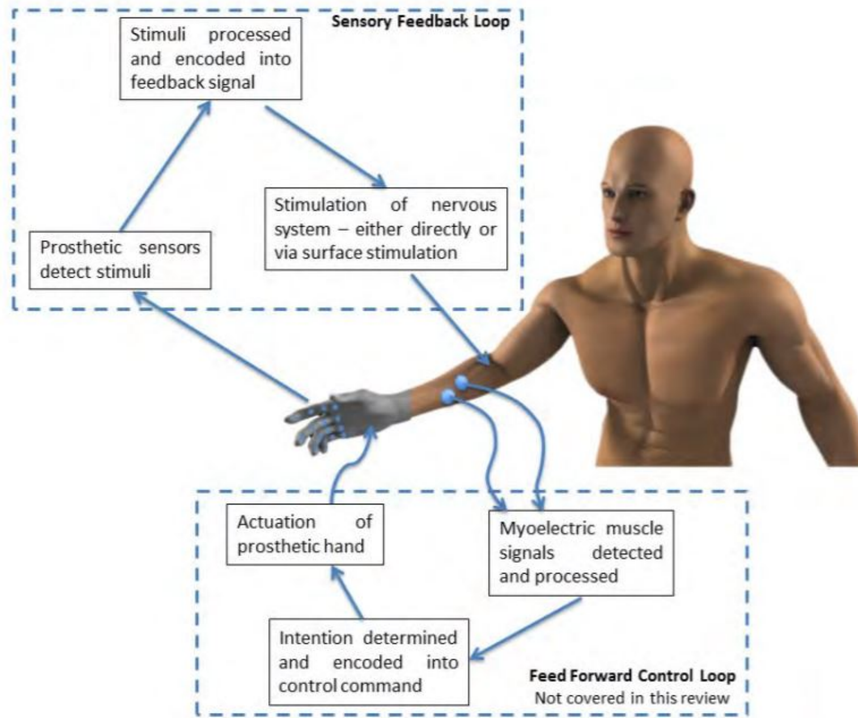


Figure D.1: Sensory feedback and feed-forward control loops [69].

methods include systems with devices placed on the surface of the skin. The sensation provided can be in the form of vibration, mechanical pressure, audio feedback, use of temperature, etc. Nevertheless, the interpretation of this kind of signals is not always intuitive [69]. On the other hand, invasive methods are mostly at the experimental stages because of the risk of side effects. This leads to a trade-off between accuracy and invasiveness.

Appendix E

Adam's Hand (BionIT Labs)

The Adam's Hand is a transradial myoelectric prosthesis developed by the start up BionIt Labs (**Figure E.1**). The name Adam's Hand stands for *"A Dialogic Adaptive Modular Sensitive Hand"*. The first model was designed in 2018 but is still not current commercialized. This non-invasive prosthesis uses a MYO armband to collect the myoelectric signals from the muscles.

Figure E.1: Adam's Hand, BionIT Labs [70].

Thanks to sensors placed on each finger, the hand provides a pressure and temperature feedback. Additionally, a touch screen is integrated in the arm allowing the patient to interact easily with his/her prosthesis.
Adam's Hand has the particularity to have 15 DoFs, 3 per finger, activated only with **one DC motor** [31]. The great advantage of reducing the number of actuators is that the device is much lighter. There are also two servomotors to actuate the wrist movements: flexion/extension and pronation/supination. A servomotor is composed of a motor and a sensor that gives position feedback. It allows a really high degree of precision for the angular/linear position, velocity and the acceleration.

Adaptive mechanism

An adaptive mechanism is developed in the Adam's Hand (**Figure E.2**). The fingers adapt themselves automatically to the shape and dimension of the object. The idea is that if one finger is blocked when it touches an object, the other fingers continue to move until all of them are blocked. The force is then distributed equally among the five fingers [14].

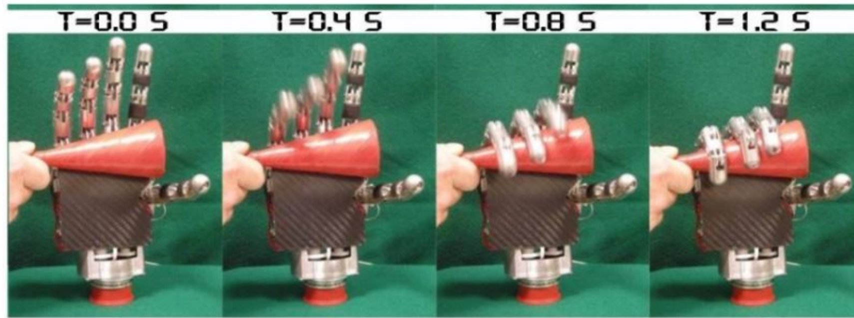


Figure E.2: Example of adaptive mechanism: SmartHand prototype [15].

Electronic modules

Figure E.3 shows the system to process the data in Adam's Hand in its entirety. Once the muscle contractions from the arm are collected (input), the MYO armband sends it by Bluetooth Low Energy (BLE) connectivity to the electronic board. The electronic board is placed into the socket of the prosthesis. The eight signals are sampled with a 200 Hz frequency.
The electronic board also receives data from the temperature and force sensors placed on each fingertip. In general the temperature varies slowly, so it would be useless to deal with high frequency samples. That is why the sample rate is around 1 Hz. Regarding the force signals, 50 Hz sample rate is used.
The DC motor and the two servomotors that actuate the fingers and wrist respectively are placed on the electronic board. They are simply connected with wires [71].

The signals are then transmitted to the Raspberry Pi board via serial connection. The Raspberry sends the data through a WiFi connection to a cloud controlled by an Orthopedic technician. The touch screen display is connected to the Raspberry so as all the information can be visualized and managed directly.

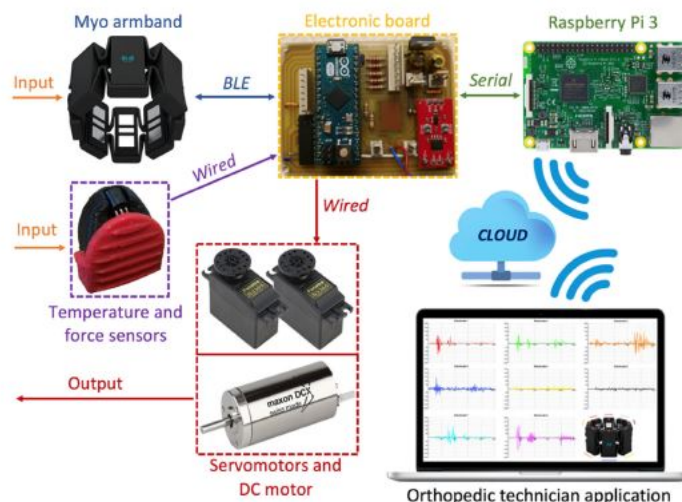


Figure E.3: Electronic modules used in the Adam's Hand [71]

MYO armband

Adam's Hand uses the myoelectric signals from the muscles collected by the MYO wireless armband. This device was developed by Thalmic Labs in 2014. There are 5 patterns that MYO recognises by default (**Figure E.4**): open, wave out, wave in, fist and pinch. A Machine Learning algorithm is implemented in order to guess the movement on the basis of the EMG signals received. It is made of [72]:

Figure E.4: Myo armband [72].

- Eight electromyography (EMG) electrodes to register the muscle activity.
- Nine-axes inertial measurement unit (IMU): three-axes gyroscope, three-axes accelerometer and three-axes magnetometer to compute the forearm movements in the three-dimensional space.
- An electronic control board embedded involving an amplifier to increase the EMG signals, a Bluetooth low energy chip, a vibration motor to provide feedback, a micro-USB connector and an antenna which transmits the data.
- Two rechargeable lithium batteries with a 5V source.

Appendix F

Visual Support used during the VR Session

F.1 Presentation slides and videos of the 3 prostheses

The following slides are written in French because all the subjects are French-speaking. The links to access the videos shown to the subjects can be found in the caption of the **Figures F.1, F.2 and F.3**.

Figure F.1: Presentation Slide of the Greifer. The presentation video can be accessed at the following link: **Electric Greifer - Tutorial: different functions | Ottobock**

Figure F.2: Presentation Slide of the Bebionic. The presentation video can be accessed at the following link: **Bebionic hand prosthesis - Stephens Story | Ottobock**

Figure F.3: Presentation Slide of the i-Limb. The presentation video can be accessed at the following link: **i-Limb Video**

F.2 Explanation slides of the 3 prostheses

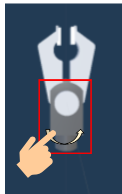
GREIFER - Explications

1

Ouvrir la pince (Extension de la main)

Fermer la pince (Flexion de la main)

2



Rotation du poignet:

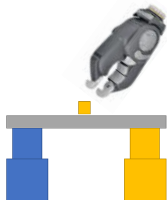
toucher le poignet avec l'autre main.

3

GREIFER – Tâches

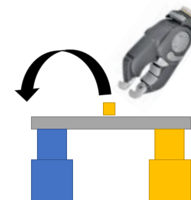
4

Construisez un château de cubes!



5

Une fois le château construit, faîtes tomber le petit cube



6

BEBIONIC - Explications

7

Initier le mouvement

Flexion de la main

Revenir à la position intiale

Extension de la main

8

Position initiale: Mode 1

Position initiale: Mode 1

Position initiale: Mode 2

Fermeture main

Ouverture main

Changement de modes

Fermeture main

9

Les 8 positions de main sont réparties en 4 groupes

Groupe 1

Groupe 3

Groupe 2

Groupe 4

10

Changement au sein d'un même groupe

2X

Double signal d'ouverture quand la main est déjà ouverte

11

Pouce position A **Pouce position B**

Groupe 1

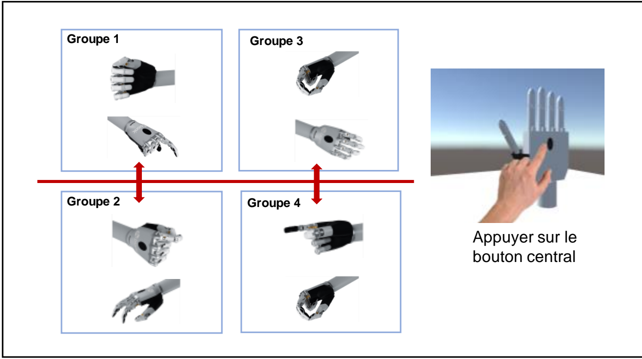
Groupe 3

Groupe 2

Groupe 4

Toucher la base du pouce pour changer de position

12



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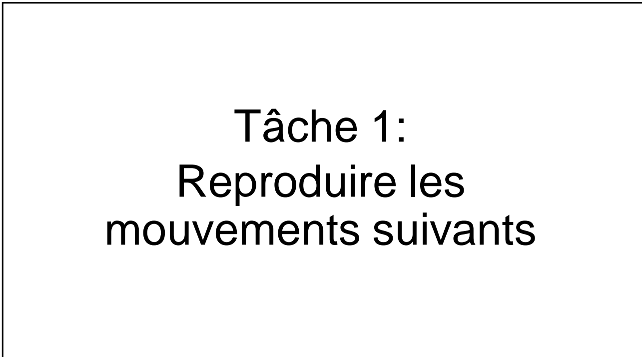
14



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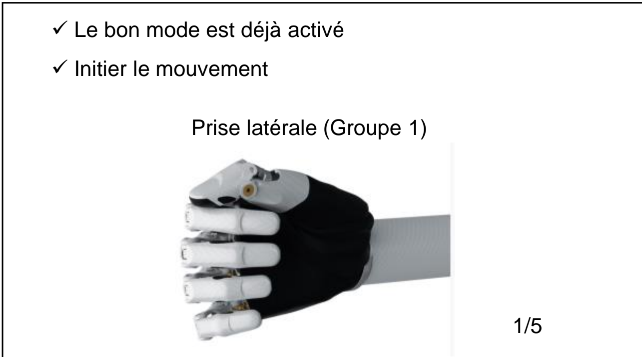

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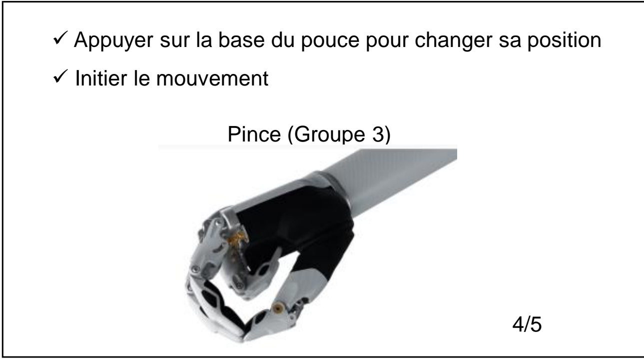
18



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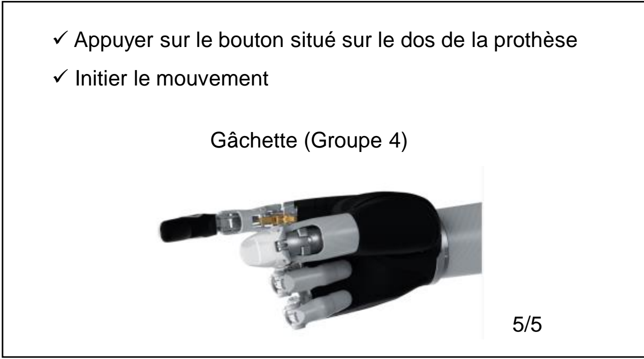
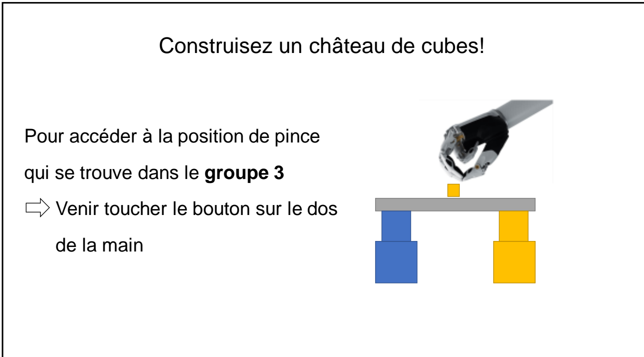


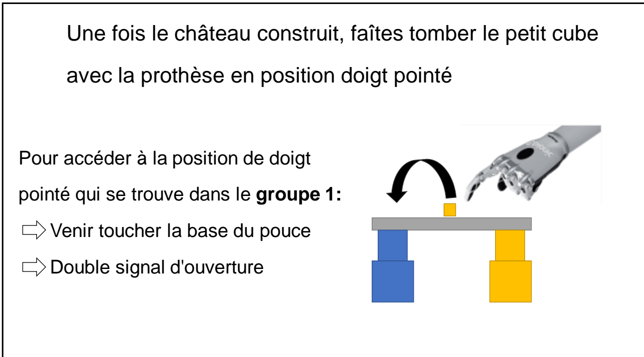
20

Tâche 2: Manipuler les blocs

21



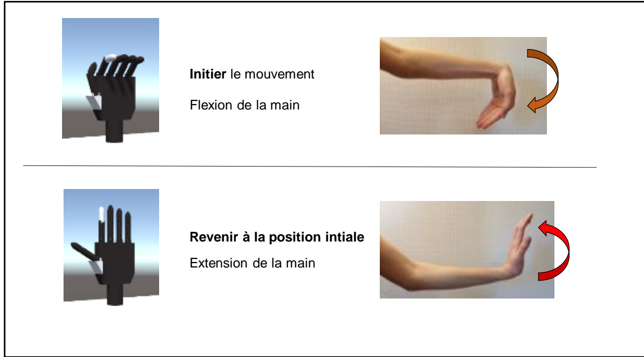
22



23

ILIMB - Explications

24



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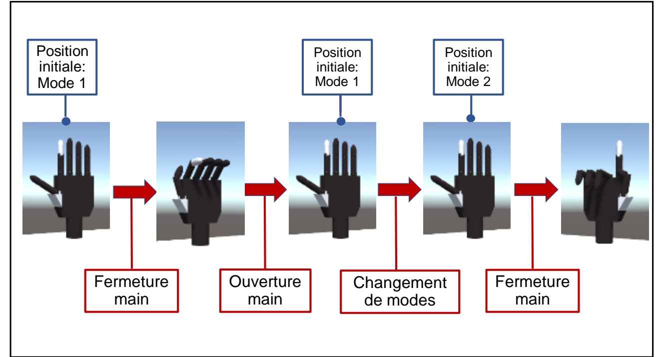
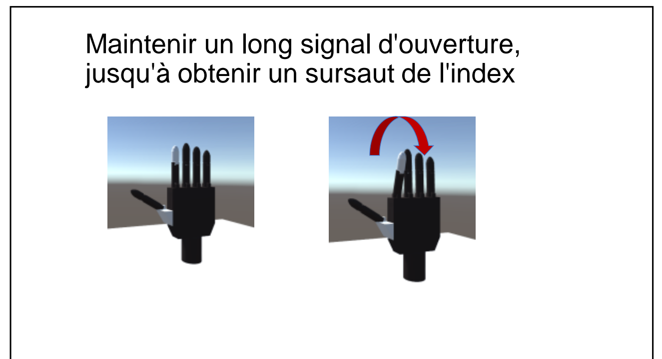


26

Méthode 1
Pour changer le mouvement de main initié

27



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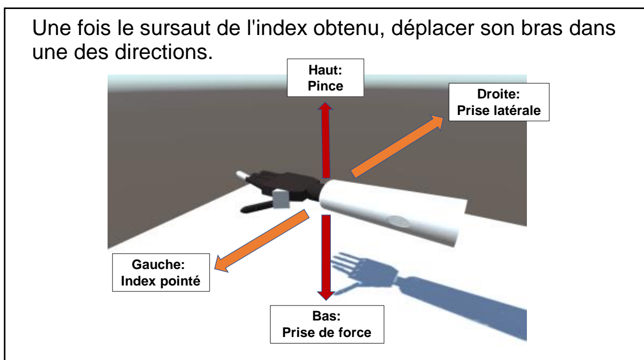

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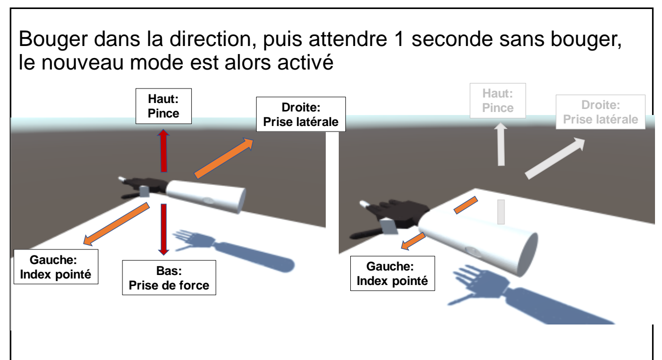
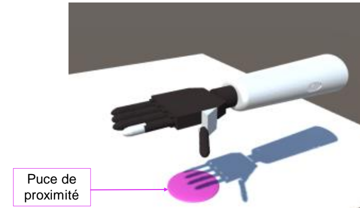


30

Méthode 2:
Pour changer le mouvement de main initié

31

Puce de proximité: Accéder à un mouvement spécifique en plaçant sa main au-dessus de la puce



Note: le sursaut de l'index ne doit pas être effectué pour ce changement de position

32

ILIMB - Tâches

33

Tâche 1:
Reproduire les mouvements suivants

34

- ✓ Le bon mode est déjà activé
- ✓ Initier le mouvement

Prise latérale

1/5

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- ✓ Provoquer le sursaut de l'index : mouvement d'ouverture
- ✓ Déplacer vers le **gauche**
- ✓ Initier le mouvement

Index pointé

2/5

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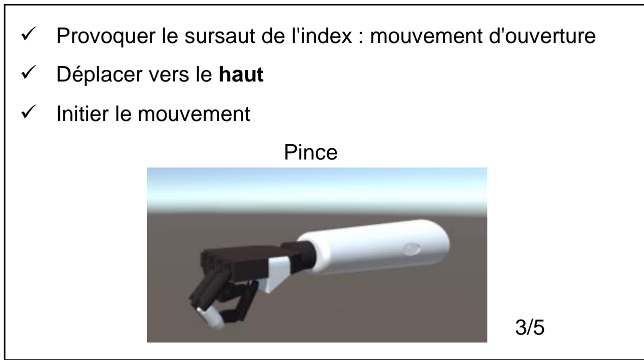
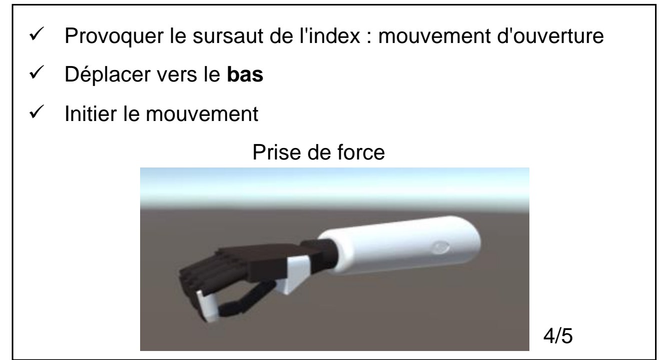
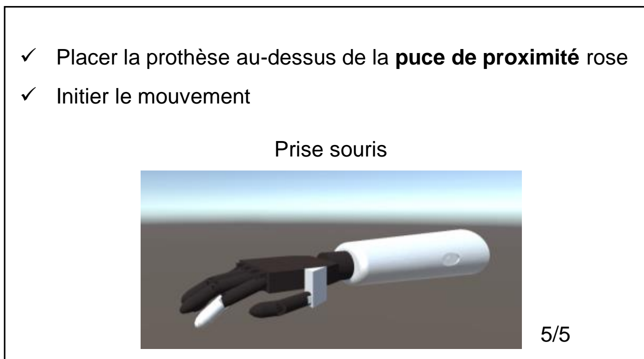


37



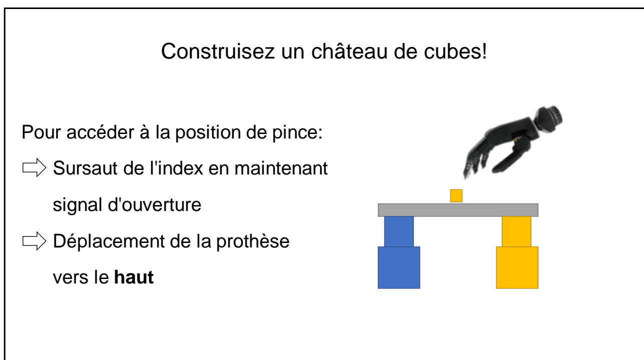
38



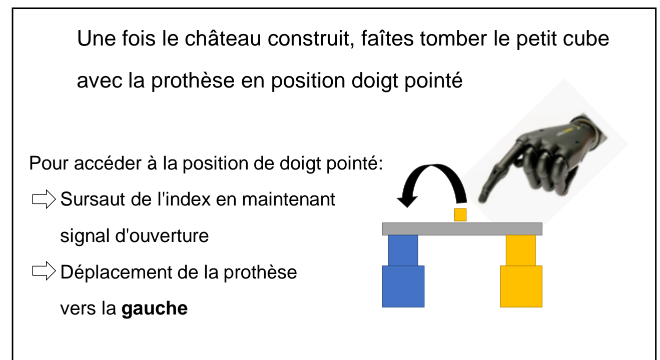
39

Tâche 2:
Manipuler les blocs

40



41



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Appendix G

Experimental Setup: Additional Information

G.1 Setup used during the development of the tool

The setup used in order to develop the tool was slightly different from the final one. **Figures 4.1 and G.2** illustrate it. The arduino code remains the same.

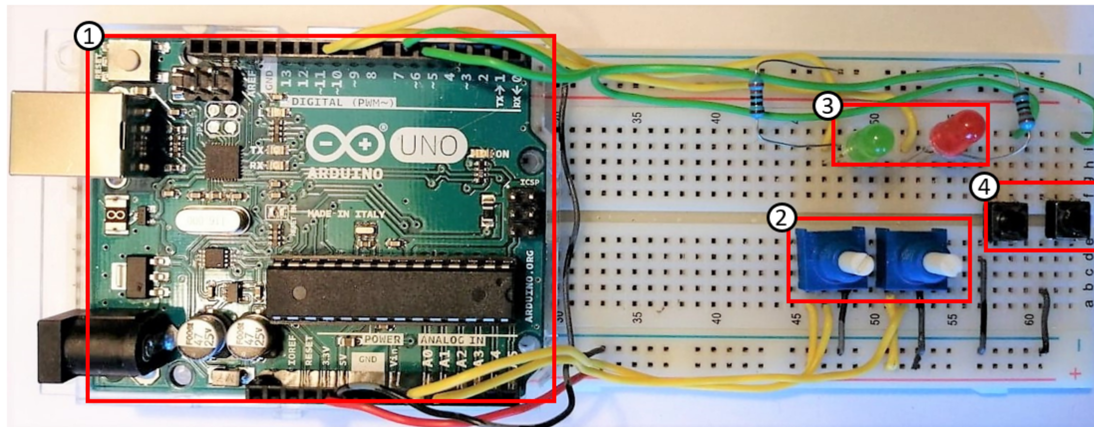

Figure G.1: Picture of the setup used for the development of the tool. (1) Arduino Uno, (2) Electrode connection placement, (3) Leds, (4) Buttons.

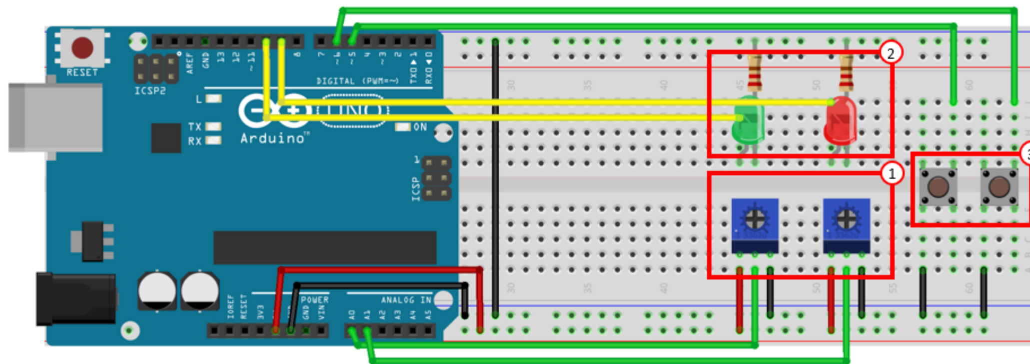

Figure G.2: Illustration of the setup used for the development of the tool (like **Figure G.1**). (1) Potentiometer, (2) Leds, (3) Buttons. Drawn with *Fritzing*.

G.2 Computer references

Acer Aspire7

- Intel Core i7 2.2GHz with Turbo Boost up to 4.1GHz
- NVIDIA GeForce GTX 1060 with 6GB GDDR5 Dedicated VRAM
- 16GB DDR4 Memory
- 256GB PCIe NVMe SSD + 1000GB HDD

G.3 Additional files

A brief description of the architecture of our files is detailed bellow. For additional questions of use, please contact the authors.

- `UnityProject>Assets`: the Unity project used for development
  - `Images`: The images used for the scenes *MainMenu* and *ThresholdAdjustment*.
  - `Scenes`: The four scenes: *MainMenu*, *ProsthesisSelection*, *TestRoom* and *ThresholdAdjustment*
  - `Prostheses`
    - `ForeArm`: The model of the Forearm.
    - `Greifer`: All the files used for the Greifer prosthesis.
      - `GreiferSlide`: Slides displayed for explanation and tasks.
      - `PrefabGreifer`: All files for the prosthesis GO and control.
    - `Bebionic`: Content hierarchy similar to the Greifer file.
    - `ILimb`: Content hierarchy similar to the Greifer file.
    - `Audio`: Contains all files for playing sounds (used for auditory feedback)
  - `Scripts`: All the scripts, except the ones for prosthesis control
  - `SteamVR`, `SteamVR_Input`, `StreamingAssets`: imported SteamVR assets. Required for VR.
  - `_VRHands`: Imported package for the model of the left hand.
- `UnityApp>Master_Thesis_VRforULA_june2020.exe`: The executable file that contains the project

- **`ArduinoInterface`**: Script to load on the Arduino micro-controller for interfacing the electrodes.

Appendix H

Opinion Survey

H.1 Questions

Two opinion surveys were designed specially for this experiment, they can be accessed at the following links:

Online Opinion Survey: Before VR session

Online Opinion Survey: After VR session

The following pages present the survey. Differences between the before/after VR session surveys are precised. The numbering differs between the two surveys but the numbering used in the main text, such as "from Q3 to Q14", refers to the Survey after VR session.

Questionnaire d'opinion

Le but de ce questionnaire est de recueillir votre sentiment personnel concernant les 3 prothèses. Il n'existe pas de bonne ou de mauvaise réponse.

1. Notez les deux premières lettres de votre prénom en majuscule, suivi des deux derniers chiffres de votre année de naissance, suivi des deux dernières lettres de votre nom de famille en majuscule (ex: Bernard Lhermitte né en 1977 = BE77TE). *

Entrez votre réponse

2. Dans quel ordre avez-vous testé les prothèses dans la réalité virtuelle ? *

	Main Bebionic	Main I-Limb	Pince Greifer
En première	○	○	○
En deuxième	○	○	○
En dernière	○	○	○

La question 2 est remplacée par les suivantes lors du PREMIER questionnaire, AVANT que le sujet ait pu tester la VR.

2. Etes-vous droitier ou gaucher ? *

○ Droitier

○ Gaucher

3. Quelle est votre profession ? *

Entrez votre réponse

---

3. Classez les 3 prothèses myoélectriques selon leur esthétisme (de la + esthétique à la - esthétique) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

4. Classez les 3 prothèses myoélectriques selon les possibilités qu'elles pourraient vous apporter au quotidien (de la + utile à la - utile) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

5. Classez les 3 prothèses myoélectriques selon leur design (de la + belle à la - belle) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

6. Classez les 3 prothèses myoélectriques selon leur complexité (de la + complexe à la - complexe) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

7. Classez les 3 prothèses myoélectriques selon leur fonctionnalité (De la + fonctionnelle à la - fonctionnelle) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

8. Classez les 3 prothèses myoélectriques selon leur originalité (De la + originale à la - originale) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

9. Classez les 3 prothèses myoélectriques selon la motivation que vous avez d'apprendre à la maitriser (De celle qui vous motive le + à celle qui vous motive le -) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

10. Classez les 3 prothèses myoélectriques selon leur aspect robuste (De celle qui a l'air le + robuste à celle qui a l'air le - robuste) *

- Main Bebionic
- Main I-Limb
- Pince Greifer

11. Classez les 3 prothèses myoélectriques selon leur aspect innovant (De celle qui parait la + innovante à celle qui parait la - innovante) *

Main Bebionic

Main I-Limb

Pince Greifer

12. Classez les 3 prothèses myoélectriques selon leur aspect intuitif (De celle qui vous parait la + intuitive à celle qui vous parait la - intuitive) *

Main Bebionic

Main I-Limb

Pince Greifer

13. Classez les 3 prothèses myoélectriques selon leur aspect fragile (de celle qui vous parait la+ fragile à celle qui vous parait la - fragile) *

Main Bebionic

Main I-Limb

Pince Greifer

14. Classez les 3 prothèses myoélectriques selon l'envie que vous avez d'apprendre à l'utiliser (De celle qui vous donne le + envie d'apprendre à celle qui vous donne le - envie d'apprendre) *

Main Bebionic

Main I-Limb

Pince Greifer

15. En utilisant la pince Greifer, quelles sont les activités de la vie journalière qui vous semblent réalisables ? *

- [ ] Manger
- [ ] Vous habiller
- [ ] Utiliser votre téléphone
- [ ] Faire vos courses
- [ ] Cuisiner
- [ ] Nettoyer et entretenir votre maison
- [ ] Faire vos lessives
- [ ] Vous déplacer (vélo, voiture, trotinette, bus, ...)

16. En utilisant la main Bebionic, quelles sont les activités de la vie journalière qui vous semblent réalisables ? *

- [ ] Manger
- [ ] Vous habiller
- [ ] Utiliser votre téléphone
- [ ] Faire vos courses
- [ ] Cuisiner
- [ ] Nettoyer et entretenir votre maison
- [ ] Faire vos lessives
- [ ] Vous déplacer (vélo, voiture, trotinette, ...)

17. En utilisant la main I-Limb, quelles sont les activités de la vie journalière qui vous semblent réalisables ? *

- ☐ Manger
- ☐ Vous habiller
- ☐ Utiliser votre téléphone
- ☐ Faire vos courses
- ☐ Cuisiner
- ☐ Nettoyer et entretenir votre maison
- ☐ Faire vos lessives
- ☐ Vous déplacer (vélo, voiture, trotinette, ...)

18. Finalement, quelle prothèse choisiriez-vous ? *

- ○ Main Bebionic
- ○ Main I-limb
- ○ Pince Greifer
- ○ Aucune

Question seulement posée lors du SECOND questionnaire, APRES que le sujet ait pu tester la VR.

19. Selon vous, la réalité virtuelle a-t-elle eu une influence sur votre choix de prothèse ? *

- ○ Oui
- ○ Non

H.2 Full results (from Q15 to Q17)

	Greifer		i-Limb		Bebionic	
Activity	Before	After	Before	After	Before	After
Dress	20 %	60 %	60 %	100 %	100 %	100 %
Cook	60 %	40 %	100 %	100 %	100 %	100 %
Travel (bike, car, ...)	40 %	60 %	60 %	100 %	80 %	80 %
Clean and maintain a house	100 %	80 %	80 %	100 %	100 %	80 %
Eat	60 %	40 %	100 %	100 %	100 %	100 %
Shop	100 %	80 %	80 %	100 %	100 %	100 %
Do the laundry	40 %	60 %	80 %	100 %	100 %	100 %

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