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

Proof of Concept

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Abstract

Nowadays, prostheses have a great impact on the daily life of upper limb amputees (ULA) since they allow them to perform a large number of tasks. However, the selection of the most suitable prosthesis is becoming more and more difficult due to the growth of new technologies that increase the quantity of prostheses available on the market. Moreover, this difficulty is accentuated by the fact that patients do not have the opportunity to test them.

The aim of this study is to facilitate the choice of prosthesis. For this purpose, a series of experimental trials was conducted using a tool that offers ULA patients the possibility to virtually test prostheses. The study included 12 able-bodied participants and 1 ULA participant. The virtual environment was built with Unity and virtual control of the prostheses is enabled by 2 electrodes placed on the forearm or residual limb. Currently, 3 commercially available myoelectric prostheses are implemented in the prototype.

Based on this experience, a comparison of the different implemented prostheses on the basis of their functionality, usability and learnability has been made. Moreover, the impact of virtually testing on the prosthesis chosen by the subject was highlighted.

This project is a promising proof of concept, with room for improvements, to help the ULA community.

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List of abbreviations

ANOVA Analysis Of Variance

BFB Biofeedback

DIP Distal Interphalangeal

DMP Data Management Plan

DoF Degrees of Freedom

EMG Electromyography

GO Game Object

HMD Head-Mounted Display

MCP Metacarpophalangeal

MS Mean Squares

PIP Proximal Interphalangeal

RoM Range of Motion

SS Sum of Squares

SUS System Usability Scale

TM Trapezo-metacarpal

ULA Upper Limb Amputee

VR Virtual Reality

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Introduction

Around 3 million people worldwide are **upper limb amputees** (ULA) and not everyone has the opportunity to obtain a prosthesis. Thanks to the advancement of technology, patients have the choice between different types of prostheses. However, the most popular are the **passive** prostheses with a purely aesthetic function [1].

According to Esquenazi [2, 3], in the case of an amputation, patients go through 9 rehabilitation phases during which a choice of a prosthesis deemed most suitable for their daily life will have to be made. This choice may be influenced by various factors among which the cost, complexity of use and health insurance coverage. When people lose a limb, their daily life is strongly impacted, especially in terms of autonomy and professional life, even more so for those doing manual work.

In order to improve their quality of life, technological advances have allowed the appearance of advanced **bionic** prostheses which have gradually replaced the simple hook prostheses. These new prostheses can be powered either mechanically or electrically. In this work, we will focus on **myoelectric prostheses**, belonging to the second type, for which the reception of electrical signals transmitted through the muscles is possible thanks to the placement of sensors on the residual muscles [4]. However, due to the large number of these prostheses, which is increasing over time, the selection of the most suitable prosthesis is becoming more and more difficult. In addition, various external factors complicate this selection, such as the lack of precise knowledge of the patient's needs or the impossibility of testing the different prostheses. Indeed, patients make their choice only based on theoretical descriptions, and the complexity of myoelectric prostheses can lead to a rejection of the selected prosthesis [5].

The **objective** of this thesis is to contribute to solve this selection and rejection problem. The proposed solution is the creation of a virtual tool allowing patients to test different prostheses through the execution of virtual tasks. It aims to get more familiar with the prostheses, understand their functioning and control.

The first chapter of this report focuses on the broad understanding of upper limb amputation and virtual reality (VR). Then, a state of the art is presented in the second chapter, summarizing existing virtual systems and their applications in the field of ULA. Chapter 3 provides an overview of the work done during the thesis, from a description of the experimental trials to a detailed description of the architecture and the functioning of the system. Presentation of the collected data and the related analysis is shown in chapter 4. Finally, in the chapter 5, the interpretation of the results is discussed and areas for future improvement are suggested.

Chapter 1

Background

To grasp the essence of this work, it is necessary to first comprehend the larger sense of upper limb amputation and virtual reality. This chapter aims to set the framework for those 2 concepts. First, by providing a global description of the upper limb, its amputation and myoelectric protheses. Then, concepts such as virtual reality, serious games, usability and learnability are introduced. To finish with a detailed description of the objective and hypothesis of this work.

1.1 Upper limb

1.1.1 Kinematic

Hand kinematics must be understood in order to comprehend how a prosthesis attempts to mimic real hand functions. The study of hand and wrist motions is developed in this section by taking a closer look to **degrees of freedom** (DoFs) and **ranges of motion** (RoMs).

A joint's RoM is its extent of movement, measured in degrees of a circle. It's important to distinguish between passive and active RoMs. A passive RoM is obtained when an external force induces joint action, while an active RoM is obtained when moving oneself. As shown in **Figure 1.1**, the wrist has 3 DoFs: flexion/extension, ulnar/radial deviation, and finally, supination/pronation. **Table 1.1** summarizes the RoM for each movement of the wrist, i.e 2 movements per DoF.

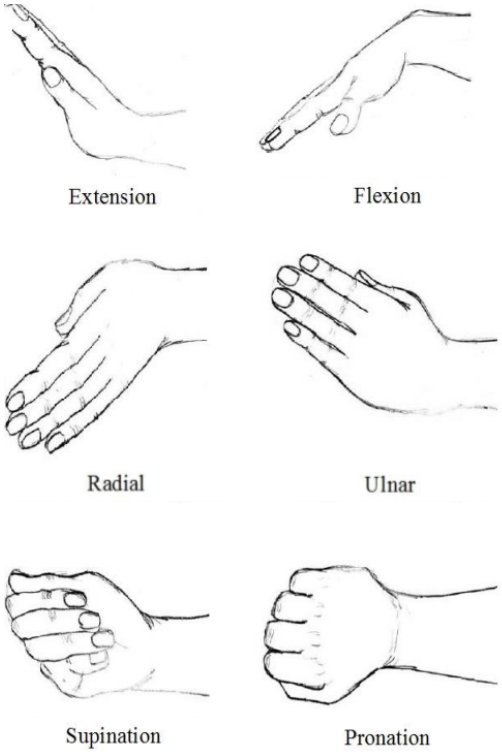


Figure 1.1: Movement of the wrist. Adapted from [6].

	Flexion	Extension	Radial dev.	Ulnar dev.	Supination	Pronation
RoM	70°	90°	20°	50°	80°	80°

Table 1.1: Active RoMs of the wrist joints [6].

Figure 1.2: Finger motions : flexion/extension and abduction/adduction [7].

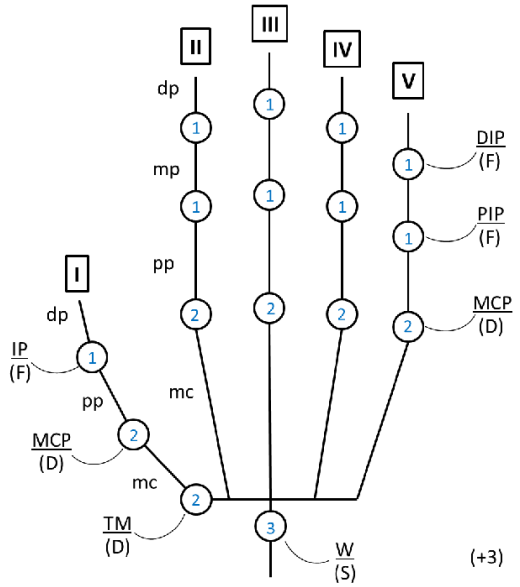


Figure 1.3: Palmar view of the right hand - 27 DoFs [8]. Fingers are numbered from I to V. The circled numbers represent the number of DoFs of each joint. The bones of the hand are indicated with the following abbreviations: dp= distal phalange, mp= middle pha- lange, pp= proximal phalange, mc= metacarpus.

The joints of the fingers are more complicated. Establishing a kinematic model of the hand reveals that each finger has 4 DoFs and the thumb has 5. Each finger is made up of two **interphalangeal** (IP) joints: the **distal** (DIP) and the **proximal** (PIP), as seen in **Figure 1.3**. Flexion/extension is possible for these joints (2 DoFs). Moreover, it is made of the **metacarpophalangeal** (MCP) joint, which causes flexion/extension and abduction/adduction (2 DoFs). There is just one IP joint and one MCP joint on the thumb. The **trapezio-metacarpal** (TM) joint, on the other hand, allows for flexion/extension and abduction/adduction (2 DoFs) [9].
The TM joint in the thumb has a unique structure known as a saddle-shaped joint. This shape enables the thumb to do an opposition motion, which corresponds to the thumb's ability to touch the other fingerprints.
Futhermore, the translation of the wrist can add 3 DoFs, indicated by a (+3) in **Figure 1.3**, since the hand can move in all the planes of a 3D space.

Based on the previous explications, we can compute the DoFs of the hand gesture to show its complexity. As explained the wrist has 3 DoFs while each fingers has 4 DoFs and the thumb has 5. Adding the 3 DoFs of the wrist's translation, it leads to 27 DoFs in total. However, the model used in **Figure 1.3** is simplified and does not take into account all the muscles and tendons in the hand. With a completely detailed model,

the hand gesture has more than 60 DoFs in total [9].

This complexity shows that the brain would not likely activate each muscle and tendon for a specific movement, but rather follows a pattern. This phenomenon is known as **muscle synergy**. It is defined as the coordinated recruitment of a group of muscles with specific activation balances or specific activation waveforms. Recent experiments have indicated that many motor behaviors are controlled through the flexible combination of a small number of muscle synergies. This mechanism is believed to simplify the selection of the appropriate muscle commands for a given behavioral goal [10].

Some movements are more complex than others and require the use of more muscles. Hand movements can be classified into two groups. The first is referred to as global prehension. The thumb's skill is to oppose the other digits. The majority of the actions performed by the hand are grasping operations. The second group considers the finer movements. They are more precise and necessitate the need to shift each finger individually, like clicking on a keyboard or playing the piano. Since they are the most useful, many of the patterns introduced in the prosthesis contain global prehension.

1.1.2 Anatomy and physiology

The upper limb is the limb of the body extending from the deltoid region to the hand. It is specialized for functions requiring great mobility, such as grasping and manipulating [11]. The upper arm, forearm, and hand are the three separate regions of the upper limb. In the frame of this research, we focus on the anatomy and physiology of the forearm.

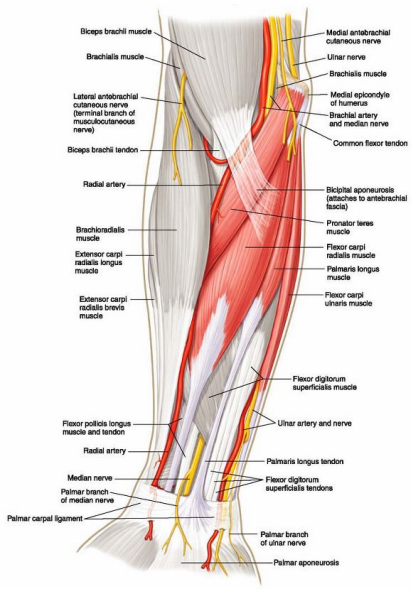


Figure 1.4: Forearm anterior compartment [12]

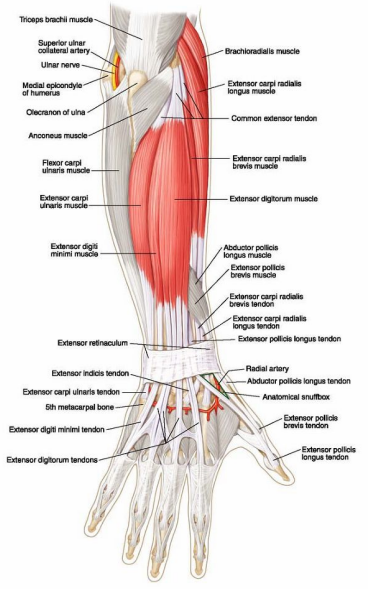


Figure 1.5: Forearm posterior and lateral compartment [12]

Anatomically, the flexor muscles of the forearm anterior compartment, shown in **Figure 1.4**, enable wrist flexion, wrist ulnar deviation and finger flexion, while the

wrist extension and finger extension is enabled by most extensor muscles of the forearm posterior and lateral compartment, shown in **Figure 1.5**. Only the brachioradialis and the extensor carpi radialis longus enable the wrist radial deviation instead of the wrist enxtension.

The **muscle fibers**, i.e long multinuclear cells, are the main component of every skeletal muscle of the body. Connective tissue components named fibrils, form the skeleton's structure for muscle, nerves, and blood vessels. Endomysium is the name given to the internal muscle skeleton that penetrates the whole muscle and surrounds the muscle fibers. Specific bundles of muscle fibers are wrapped in fasciculus, and are encased by perimysium, a delicate connective tissue layer. The fleshy part of the muscle is formed by the bundle of fasciculus, while tendons are formed as endomysium connects at both ends of the muscle [13].

Muscle innervation is a key to understand the functioning of the tool developed for this work. Most extrafusal muscle fibers are innervated by a single α-motoneuron of the anterior horn of the spinal cord. The axons of the α-motoneurons branch to synapse with several different muscle fibers. The α-motor neuron and the muscle fibers that it innervates constitute a **motor unit**. The muscle fibers innervated by different axons are intermingled to allow a more homogeneous distribution of the contractile force generated by each motor unit.

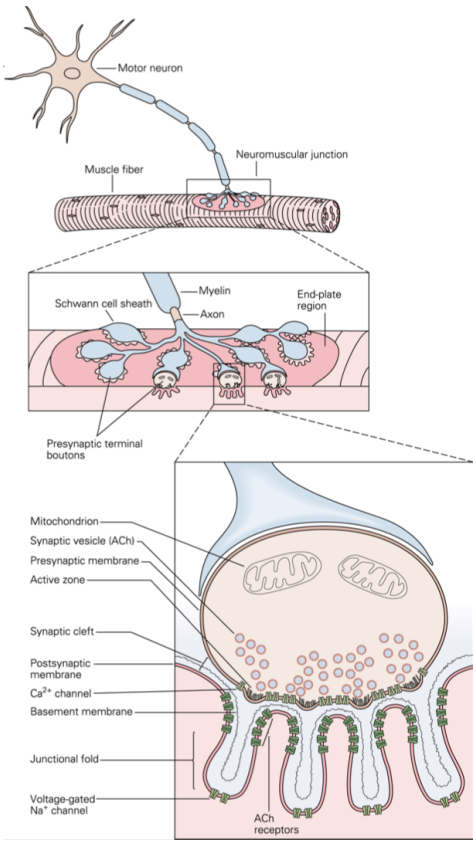


Figure 1.6: Motor unit and neuromuscular junction [14]

As shown in **Figure 1.6**, the axon endings of motor neuron axons form an **end plate**, on the cell membrane of each innervated muscle fiber, separated by the synaptic cleft. A **neuromuscular junction** is a synapse allowing connection between an axonal branch of motoneurons and a muscle fibre.

The transmission of excitation to the muscle fiber occurs in 4 steps:

- Presynaptic depolarisation and release of neurotransmitter, i.e acetylcholine in the synaptic cleft.
- Activation of receptor-gated Na+ nicotinic receptors of the postsynaptic (muscle) cell membrane. The influx of Na+ produces depolarisation, i.e end plate potential.
- If the depolarisation produced by the end plate potential is sufficient, activation of voltage-gated Na+ channels leading to the propagation of an action potential along the muscle fiber (**Figure 1.7**).
- Destruction of acetylcholine in the synaptic cleft by acetylcholinesterase.

The motor unit action potential is the summation of all action potentials generated by each muscle fibre. **Electromyography** (EMG) explores the electrical activity of the muscle using electrodes. EMG signals are basically made up of multiple motor unit action potentials superimposed on top of each other. In this work, EMG sensors are used to measure muscle control signals. Based on these signals, it will be possible to control the virtual prosthesis.

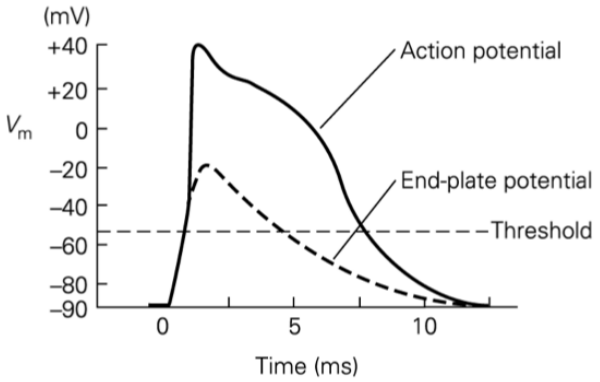


Figure 1.7: Transmission of excitation to the muscle fiber

1.1.3 Amputation

The **residual limb** corresponds to the remaining part of the limb after amputation. The residual limb allows to classify or name the amputation. The different upper limb amputation classification are shown in **Figure 1.8**. There is a distinction between transverse amputation, i.e through a bone, and disarticulation, i.e dislocating a joint, keeping the bones intact. In the frame of this work, we will focus on **transradial amputation**.

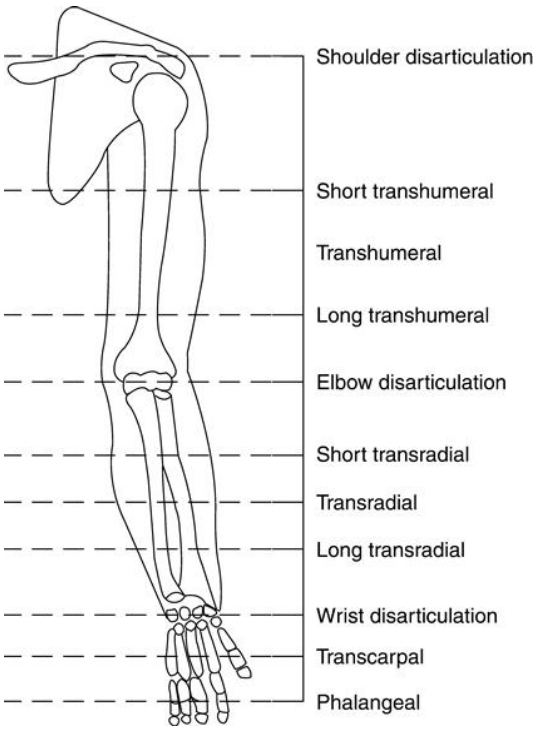


Figure 1.8: Upper limb amputation classification. [15]

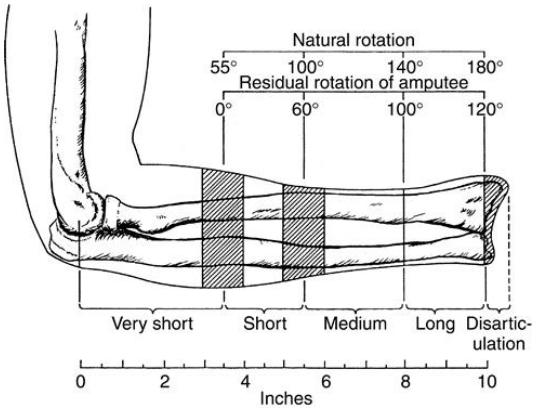


Figure 1.9: Influence of the residual limb's length. [15]

The finger, partial hand, and transcarpal level are the most distal. Wrist disarticulations are amputations that isolate the carpal bones from the radius and ulna. Transradial amputations take place inside the radius and ulna bones. The amputation is known as an elbow disarticulation when the humerus remains but the radius and ulna are removed. Transhumeral amputations are described as those that remove more than 30% of the humeral length. Shoulder disarticulations occur when less than 30% of the proximal humerus is preserved. Forequarter amputations or scapulothoracic amputations are more proximal amputations that invade the central body cavity, resecting the clavicle and inducing scapula derangement.

The amount of functional elbow flexion and forearm pronation/supination that will be maintained, regardless of prosthetic intervention, depends on the length of the residual limb for those with transverse forearm amputations. Natural anatomical movements in supination and pronation are ensured by articulations between the radius and the ulna along the entire forearm. The ability to perform and use pronation and supination during functional activities deteriorates with the decrease of residual limb's length (**Figure 1.9**). When the residual forearm is extremely short, all transverse motion is effectively lost, and active functional forearm rotation for prosthetic use is difficult to achieve.

While sufficient wound closure is the primary concern of surgeons performing upper-limb amputations, importance must be given to the possible benefits of a longer lever arm as well as an understanding of prosthesis's space requirements. As long as sufficient skin and tissue viability is not jeopardized, adequate space for a wide spectrum of prosthetic components should be considered.

According to the paper [16] from 2005, the amputee population in the United States of America (USA) would approach two million in 2020 and may potentially double by 2050. This issue affects not simply the United States, but every country in the world, developed or developing. Motor vehicle accidents (42.9%), industrial accidents (26.2%), and motorcycle accidents (21.4%) are the three most common traumas leading to amputation [17]. Moreover, traumatic amputations primarily affect the upper limbs [16]. These data tend to highlight the large proportion of upper limb amputees among the overall amputee population and more broadly among the world population.

1.1.4 Types of prostheses

There are 2 general types of upper limb prostheses, namely the passive prosthesis and the active one. According to the means of generating movement at the joints, active prosthesis can be classified into 2 categories: body-powered movement and electrically powered movement [18]. However, the functionality of these 2 categories can be combined to create another type of prothesis, called "hybrid prosthesis". Overall, upper limb prostheses can be divided into 5 categories, according to Arm Dynamics [19] and each of them has its pros and cons.

Figure 1.10: An passive arm hand system prosthesis. [20]

Passive prostheses:
These prostheses, without any active movement, are generally designed for purely aesthetic purposes and their functionality is limited to that of a simple counter-support when handling objects. They have the particularity of being light, since they do not have any motor or mechanical device, and allow to provide a surface, to stabilize or carry objects, in order to improve the daily life of a person.

Body-powered prostheses:
In order to allow functional manipulation of the elbow and hand, body-powered prostheses use a body harness and cable system. The movement of the cable and the transmission of force to the end device is done through a voluntary movement of the shoulder and/or the limb stump. This type of prosthesis is highly appreciated by people doing manual work because of its durability and the versatility offered by its mechanism allowing an intuitive control of the prosthesis as well as a force feedback via the tension in the cable. It also provides a high sensory feedback at a moderate cost and weight but requires more upper limb movement to function properly and has a poorer cosmesis.

Figure 1.11: An example of a body-powered arm hand prosthesis. [21]

Figure 1.12: An example of an electrically powered arm prosthesis. [19]

Electrically powered prostheses:
Unlike the body-powered prostheses, the movement and the power supply of the electric prostheses are provided by motors and batteries. More precisely, sensors or inputs are used to detect the movements of the muscles of the residual limb, which are then translated into electrical signals so that the desired movement can be performed using the motors of the prosthesis. They also allow more proximal coverage and a better cosmesis but require more maintenance and are heavier and more expensive.

Hybrid prostheses:
The hybrid prostheses, as already mentioned above, are a combination of body-powered

and electrically powered prostheses. Generally, this type of prosthesis is used for high-level amputations (i.e. at or above the elbow). One of its particularities is the control of 2 joints at the same time, i.e. one body-powered and the other electrically powered. Compare to a fully electrically powered prosthesis, it is lighter and less expensive since they have less EMG controlled components.

Activity-specific prostheses:
Those prostheses are designed for specific activities (hobbies, work or even sports) and can be applied to the different types of prostheses already mentioned above.

1.2 Myoelectric prostheses

In this section, a summary of 3 **myoelectric**[1] **prostheses** commercially available is made. The 3 prostheses chosen are the ones implemented in the device of last year's thesis. The three prostheses are compared in **Table 1.2** according to different criteria.

These criteria provide informations about the degrees of freedom, the dexterity and the complexity of the different prostheses. Moreover, we can notice that the 3 prostheses presented below all use 2 electrodes. Each of these prostheses will be detailed in the following sub-sections.

Name	Independent fingers	Passive movements	Actuators	Grip patterns	Electrodes
Greifer (Ottobock)	1	wrist	2	1	1-2
Bebionic (Ottobock)	4	wrist-thumb	5	14	2
i-Limb (Ossür)	5	wrist-thumb	6	24	1-2

Table 1.2: Comparison of different existing hand prostheses that are implemented in the device [22, 23, 24]

1.2.1 Greifer

Figure 1.13: *Greifer Hook*, *Ottobock* [22].

Greifer is a prosthesis proposed by the German prosthesis company *Ottobock*. The integration of a flexion as well as an extension with a quick disconnect wrist allows for an easy transition between wearing a quick disconnect hand and the prosthesis. Due to its solid grip, fast grasping speed and sensitive response, it is often used for detailed manual work or for handling heavy objects. Depending on the intensity of the signals from the residual limb muscles, the gripping force can be automatically adjusted, and the gripping speed can range from 8 to 180 millimeters per second. The maximum angle of flexion of the wrist joint is 45° in both directions, which minimizes harmful compensating movements and provides better control accuracy. The

[1]Related to an electromotive force produced by a muscle during its contraction phase.

flexion and extension adjustment is passive. It also has a lighting system via a torch integrated in the prosthesis itself. *Greifer* has the ability to rotate thanks to the cylinder located at the wrist. This pivoting is done when opening or closing the clamp or also passively to allow manual control of the movement.

Inside the socket forearm, two electrodes are fixed. Their direct contact with the flexors and extensors of the forearm allows to receive muscle signals in order to control the opening and closing of the prosthesis, by one or the other electrode, in case of a transradial amputation. In order to obtain the best EMG signals, the location of the electrodes is specific to each patient.

1.2.2 Bebionic

Figure 1.14: *Bebionic Hand*, *Ottobock* [23].

Bebionic is also a prosthesis proposed by the German prosthesis company *Ottobock*. The compatibility of its base with that of *Greifer*, which has the same forearm socket, allows for easy transition from one prosthesis to the other thanks to the same approach used by the controller. Mostly, *Bebionic* is used to facilitate the accomplishment of activities of daily living. In total, it has 14 different grip patterns and hand positions, and the users can select 8 of them that will allow them to have more stability and precision while they will be holding and manipulating objects. Each finger has individual motors to ensure their movement and to make the use of the different grip patterns and hand positions more natural and coordinated. Only the movement of the thumb is done manually. The activation of the different movements is done via 2 electrodes placed on the forearm (as for *Greifer*) and the speed is controlled in proportion with the intensity of the EMG signals. For example, the weaker the signal sent, the lower the gripping force will be and the movement will be slow in order to move fragile objects and conversely in the case where the signal sent is higher.

Grip pattern

In order to be more flexible in everyday life, *Bebionic* prothesis offers 14 different grip patterns in which 8 of them are possible with an opposite thumb position and 6 others with the thumb in lateral position (**Appendix A**).

Switching option

In order to switch between the different grip patterns, it is important to know first of all that the manual movement of the thumb gives rise to two very specific hand positions (**Figure 1.15**) and that the different grip and position models can be classified as primary or secondary depending on whether the grip is often used in everyday life (primary) or if it is a more specific grip (secondary). Pressing for less than 2 seconds the program switch, located on the upper central part of the hand, allows to switch

from primary to secondary holds and vice versa. This button also has the particularity of turning the prosthesis on and off if the user holds it down for 3 seconds. The 8 grip patterns are divided into 4 groups in which we can find 2 grip pattern in each group. In the same group, a double opening signal ("Open+Open") or a co-contraction allows to switch from one grip pattern to the other. As for the activation of the grip pattern, it is done thanks to the simple opening and closing signals, each assigned to an electrode.

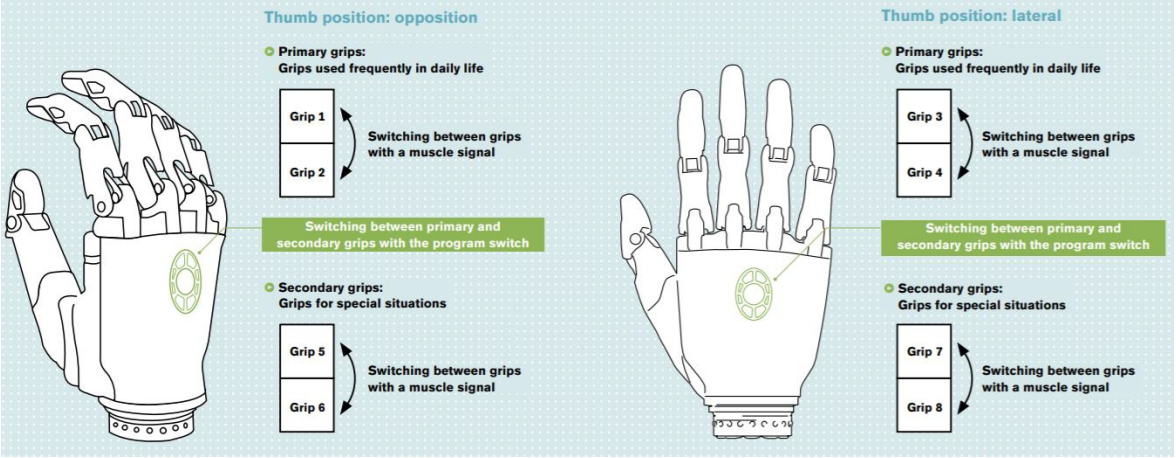


Figure 1.15: Switching between eight different grips [25].

1.2.3 i-Limb Quantum

Figure 1.16: *i-Limb Quantum*, *Ossür* [24].

i-Limb Quantum is a multi-articulated myoelectric prosthesis proposed by the Icelandic company *Ossür*, known for the development of non-invasive prostheses. Thanks to their patented i-mo^{TM} technology, this prosthesis has a simplified system to change the grip mode. Indeed, it is the displacement of the prosthesis in the 4 directions - up, down, left, right - that allows access to the various desired grips. In order to perform a wide range of daily activities, each finger is independently motorized, including the rotation of the thumb, with manual control, which, as with *Bebionic*, automatically switches from a lateral grip to an opposing grip for an optimal grip. This independent motorization also provides great dexterity as well as good coordination and finesse. In addition, wrist rotation is possible in order to perform specific tasks. As for the different grip patterns and positions, *i-Limb Quantum* has 36 (24 pre-programmed and 12 customized) and the opening and closing of the prosthesis is controlled by sending 2 EMG signals thanks to the placement of electrodes on the forearm.

Control options

i-Limb has 36 grip patterns and can be accessed through 4 ranges of control options (**Table 1.3**):

Control Options	Description
Application	The app control requires an application to select different grip patterns. It also allows to adjust the speed acceleration with a sliding bar. It is possible to get a more responsive action, a more natural look and a higher grip force potential by increasing the speed of the fingers.
Gesture control	Gesture control is active when the user holds a long opening signal to activate a jump of the index finger. Once this mode is activated, the user can move the prosthesis in one of the 4 directions (up, down, left or right) allowing him/her to access one of the 4 different gripping modes depending on the direction chosen. Depending on the user's needs, the grips programmed for each direction can be customized and the activation of the gesture control can also be done using a co-contraction (this parameter can be modified using the applications).
Proximity control	Grip chips are small Bluetooth chips. The passage of the i-limb hand close to it generates a modification of the programming of the prosthesis allowing to change the gripping mode. Mainly, the grips chip is placed in convenient locations to access an optimal grip at a certain place to perform particular tasks (for example, near a desk with a computer to pass in the "Mouse Grip"for computer mouse control).
Proximity control	Access to an automated grip can be achieved by triggering 4 different specific muscle signals: open hold, double or triple pulse (contraction) or cocontraction.

Table 1.3: Control Options [26].

Grip activation control

There are 3 different ways to control the *i-Limb* hand grip:

- **Auto-grasp:** auto-grasp uses sensors to know when an object is sliding in order to adapt the grip force of the prosthesis.
- **Velocity control:** the amplitude of the EMG signals emitted by the forearm muscles allows to control the speed of the fingers movement. This speed control is proportional to the amplitude.
- **Vari-grip option:** the closing command allows to control the grip force of the prosthesis. This force control is also proportional with the command.

i-Limb Wrist (wrist control)

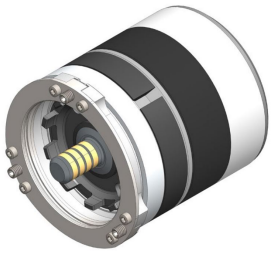


Figure 1.17: *i-Limb Wrist*, *Ossür* [27].

In order to preposition the wrist and hand during different daily activities, the *i-Limb Wrist* (**Figure 1.17**) can be used. It consists of a motorized wrist rotator, controlled by the 2 electrodes placed on the residual limb, which allow to have a control of the wrist rotation [27]. This rotation control can be done simultaneously or directly.

The **simultaneous rotation** is done by the *i-Limb Wrist* on a selection of grips. Any control option (gesture, app, muscle, proximity) of the prosthesis allows the activation of the desired grip and the wrist rotates automatically and simultaneously to reach the grip in question.

The **direct rotation**, on the other hand, corresponds to a wrist movement (linked to the actions of the muscles of the user) which is totally independent of the grip change. In this case, the control of the rotation of the *i-Limb Wrist* can be done thanks to the 3 following control methods:

- **Smart Control:** an identification of muscular actions is performed during the initial configuration allowing a calibration of the prosthesis according to its user.
- **High/Low:** wrist rotation is activated when the signal sent is strong and rising, while if the signal rises slowly, hand control is activated.
- **Co-contraction:** the switch between hand and wrist control is achieved via a co-contraction (corresponding to a fast and simultaneous contraction of both muscles).

1.3 Virtual reality

This work is the result of the collaboration of 2 different fields, namely physiotherapy and engineering. This section aims to bring the context regarding the engineering point of view by introducing concepts such as virtual reality, serious games, usability and learnability.

1.3.1 Definition

Virtual reality (VR) has typically been portrayed as a technology allowing a natural extension to 3D computer graphics with advanced input and output devices. Although, this technology has recently progressed to the point that it can warrant serious engineering purposes. Even if VR is still an in-development technology, its existing state is appropriate for pursuing projects that show the viability and effectiveness of using VR to facilitate application in areas of aeronautical research, architecture, scientific visualization in medicine, defense, and education [28].

In 1989, Laniner of *American VPL Research Inc.* came up with the term "virtual reality" to describe computer simulation technology. The majority of common definition of virtual reality also applies to a specific technical framework. For example, we can cite the following definitions:

Virtual Reality is electronic simulations of environments experienced via head mounted eye goggles and wired clothing enabling the end user to interact in realistic three-dimensional situations. (Coates, 1992)

Virtual Reality is an alternate world filled with computer-generated images that respond to human movements. These simulated environments are usually visited with the aid of

an expensive data suit which features stereophonic video goggles and fiber-optic data gloves. (Greenbaum, 1992)

While these definitions differ somewhat, they both contain the concepts of technologically replicated worlds as well as "goggles and gloves" systems as a way of accessing them. As a result, these concepts are limited to these technologies. However, virtual reality may be described without relating to unique hardware, leading to notion of presence and telepresence.

The concept of **presence** is described, in the paper [29], as the ability of the users to feel that they are "being physically present" in the virtual world. Presence can be characterized as one's perception of one's physical surroundings as mediated by both automatic and regulated mental processes. The degree to which one feels involved in a simulated world rather than in one's actual physical environment is referred to as **telepresence**. Telepresence is described, in the paper [30], as the sensation of being present in a space by the use of a communication medium. In other words, "presence" refers to a person's natural awareness of their surroundings, while "telepresence" refers to a person's mediated perception of their surroundings.

1.3.2 Serious game

Serious game application areas include a wide range of industries, including health, defense, education, politics, training, and ecology, and they continue to grow. This concept interests numerous actors, each with their own approach and definition.

In the paper [31], a survey to evaluate the possible definitions of this tool was submitted to the Serious Gaming world. From the wide range of collected definitions, the following can be used to highlight the main features of Serious Games: *Serious games may be defined as utilities video games, productive in other words, whose design aims to bring about a transformation in their recipients in line, an improvement of skills (training), the adaptation to the environment (treatment of phobias), the understanding of a phenomenon (education) or greater adherence to the message (promotion, advertising, ideological video games, also known as Political games)* (Etienne Armand Amato, 2007).

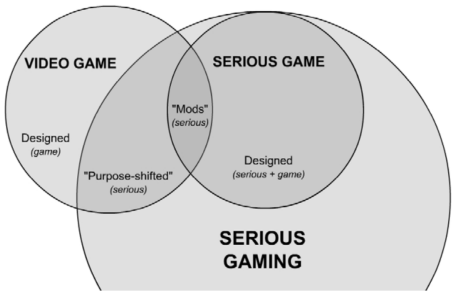


Figure 1.18: The relationship between Video games, Serious Games and Serious Gaming [32].

This description demonstrates that a serious game is both a learning process and a means of entertainment. This tool applies in almost every field and is intended for all age groups. Its relationship with video game and serious gaming is represented in **Figure 1.18**.
It can be noticed that the presence of the "serious" dimension can be claimed to be dependent on the player's subjective evaluation of the game. When a game's "seriousness" is in doubt, it is better to appeal to the creators' intent rather than the players' interpretation.

When confronted with the extensive typology of Serious Games that has been established, it is interesting to clarify this concept by putting in place a classificatory system. The **G/P/S model** [33] is a guide to classify the "Serious Games". The classification must be both by its playful dimension and its utility dimension, it is based on 3 criteria :

- **G:** Gameplay, determines if the Serious Game is based on a video Game or a video Toy. A video Game, unlike a toy, has rules that determine the player's results, whereas a toy is more akin to a sandpit, where the concept of "win" does not exist. In the case of a video Toy, "Serious Play" is used rather than "Serious Game."
- **P:** Purpose, corresponds to the functions that go beyond the designer's goal of "simple entertainment". This aspect determines whether the tool is used to broadcast a message, provide instruction, gather data, or perform multiple of these tasks simultaneously.
- **S:** Sector, identifies the area of application and market that the designer is aiming at.

These 3 aspects when combined enable to represent the "Playful" dimension (Gameplay) as well as the "Serious" dimension (Purpose + Sector) of a serious game.

1.3.3 Usability and learnability

As we are dealing with technological devices and user interfaces, concepts like **usability** and **learnability** are crucial.

Indeed, lauching products with poor usability is risky and often comes up with a price to pay, i.e expensive redesigns, poor customer experience, high volumes of customer service calls and complaints, lost user productivity and lost revenue. When we are dealing with the medical sector, the stakes are even higher. Indeed, we can cite a example found in the paper [34]. The *Association for the Advancement of Medical Instrumentation* (AAMI) sponsored a human factors conference in Washington, DC, on June 28–30, 2005. During the conference, FDA systems engineer Peter Carstensen stated that more than one-third of medical device incidents involve use error, and more than half of device recalls for design problems involve the user interface.

Definitions

In order to fully understand the notion of usability and learnability, the difference (and relationship) between both of them must be clarified. From the ISO 9241-11, usability is defined as *"The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use", (ISO 9241-11, 1998)* while learnability is regarded as *"Time of learning", (ISO 9241-11, 1998).* In the ISO 9126-1, usability is addressed as *"The capability of the software product to be understood, learned, used and attractive to the user, when used under specified conditions", (ISO/IEC 9126-1, 2000)* and learnability as *"The capability of*

the software product to enable the user to learn its application", (ISO/IEC 9126-1, 2000).

Based on previous definitions, we may conclude that usability aims to allow users to accomplish their objectives when using the system. The more usable a device is, the more likely it is that a person can continue to use it effectively for an extended period of time. Learnability, on the other hand, seeks to make it simpler for consumers to learn how to use the device. The more learnable a device is, the less time it takes for a user to understand how to do a task without being already qualified or using any documentation.

In the book [35], it is stated that focusing on learnability is better when designing the user interface for an information kiosk. Indeed, when the system is going to be used once or occasionally, the user should be able to learn it quickly. Although, for the user interface of a word processor, usability should be prioritize since the same user will use the system many times.

Relationship

Once the difference between those to notion is clear, the relationship between them must be highlighted. Learnability is seen as an active component of usability. However, there is not only one classification possible. Based on ISO 9126-1,4 (**Figure 1.19**), learnability is classified as a sub-characteristic of usability along understandability, operability, attractivness and usability. Meaning that making a system easily learnable, i.e the aim of learnability, is one of the five usability goals.

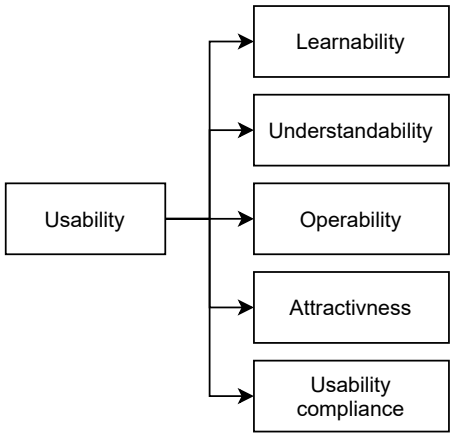


Figure 1.19: Usability Subcharacteristics (ISO 9126-1,4)

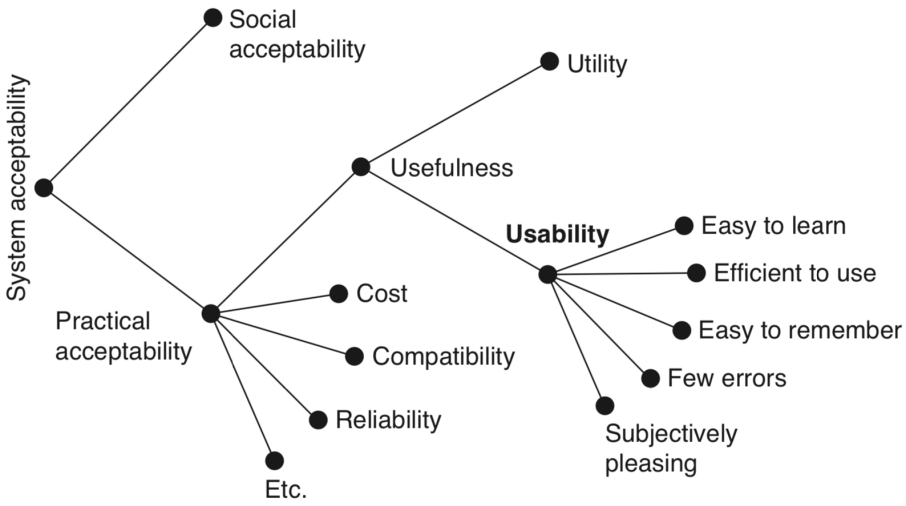


Figure 1.20: Usability as a Quality component [36]

Jakob Nielsen[2] defines usability in his book (**Figure 1.20**), through 5 quality components [36]:

- **Learnability:** the system should be easy to learn so that the user can rapidly start getting some work done with the system.
- **Efficiency:** the system should be efficient to use so that once the user has learned the system, a high level of productivity is possible.
- **Memorability:** the system should be easy to remember so that the casual user is able to return to the system after some period of not having used it without having to learn everything all over again.
- **Errors:** the system should have a low error rate so that users make few errors during the use of the system, and so that if they do make errors they can easily recover from them. Further, catastrophic errors must not occur.
- **Satisfaction:** the system should be pleasant to use so that users are subjectively satisfied when using it; they like it.

Learnability

Since most systems must be straightforward to learn and since most people's first experience with a new system is learning how to use it, learnability is in some ways the most basic usability characteristic.

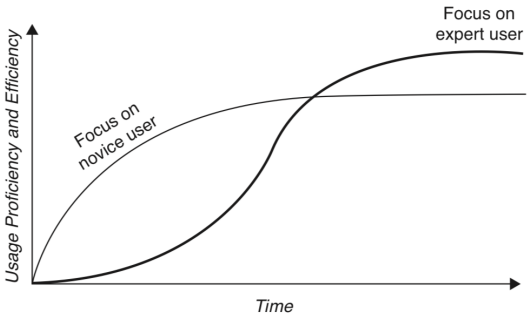


Figure 1.21: Learning curves and design tradeoffs based on aimed users, i.e novice or expert users [37]

Learning curves, as shown in **Figure 1.21**, is a quantitative testing that highlight the 3 aspects of learnability: **first-use learnability**, **steepness of the learning curve**, and **efficiency of the ultimate plateau**. The first aspect shows how easy it is to use a system the first time you try. Most of user interfaces have zero efficiency when the user starts using it. Regarding the steepness of the learning curve, it corresponds to the rate users get better with repeated use of the system. The efficiency of the ultimate plateau reflects the level of productivity achievable with the system, once it is fully learned.

Ideally, the system will excel in all three areas. However, design tradeoffs are often inevitable, and the learning curve can be shaped to appeal primarily to those consumers who have the greatest market value. For novice users, **Figure 1.21** shows the system should be easy to learn but can be less efficient. Although, for expert users, the system should be highly efficient even if it hard to learn.

[2] a leading figure in the usability field since the 1980s

1.4 Objective and hypothesis

The process of learning to use a prosthesis can be long and tedious, especially for ULA people. It has been pointed out that upper limb amputees are less likely to use their prosthesis on a daily basis compared to lower limb amputees [38]. In the ULA population, 1 in 4 adults and 1 in 2 children experience prosthesis rejection [39]. The characteristics of the patient, the level of amputation, the prosthesis chosen and the rehabilitation process will all contribute to these high rejection rates [5]. In particular, this last factor can be lengthy and complicated for more advanced prostheses such as the **myoelectric prostheses** described in the **Section 1.2**. Such prostheses are not intuitive and therefore require a significant learning effort on the part of the ULA person, which sometimes results in abandonment and rejection of the prosthesis, thus diminishing their quality of life.

As introduced in the **Section 1.1.3**, the proportion of ULA people in the amputee population is not negligible, e.g almost 1/3 for the USA [16]. Such a high rate of prosthesis rejection due to abandonment or wrong choice of prosthesis for such a population therefore generates a lot of loss. It is not without reason that the US budget for amputations in 2009 was around 8.3 billion dollars [40].

This current problem was the trigger for this thesis. In order to decrease the rejection rate of prostheses, this work aims to develop a tool offering ULA patients the opportunity to test the functionalities of the different commercially available myoelectric prostheses. This additional knowledge would be added to the theoretical explanations of the prostheses provided by the manufacturers in order to help amputees make the most suitable choice.

In order to be able to test the functionalities of the different prostheses, the developed tool uses **virtual reality**. As explained in **Section 1.3**, VR allows to feel physically present in a virtual environment thanks to the "*sense of presence*" [29]. The opportunity to move in the environment and interact with objects to test the prostheses gives all its sense to the use of VR. Therefore, it is crucial to replicate as well as possible the functionalities of the different myoelectric prostheses. A choice was made on the commercially available prostheses that were implemented in the serious game. The 3 prostheses that were modeled are the one presented in **Section 1.2**, namely *Greifer*, *Bebionic* and *i-Limb*. These 3 prostheses work by using 2 EMG surface electrodes, placed on the patient's forearm, which collect signals from the muscles.

This work is a continuation of a work that started in 2019. It is a **proof of concept**, i.e the goal is to demonstrate that the concept is feasible. **Two hypotheses**, i.e primary and secondary, are aimed to be validated during this procedure. The first one concerns the selection of the most adapted myoelectric prosthesis according to their "virtual" usability and learnability. The second one concerns the impact of the virtual testing of the prosthesis chosen by the subject.

Chapter 2

State of the art

In order to have a good foundation to reach the objectives of this work, it is important to look at the existing tools mixing upper limb amputation and virtual reality. This chapter aims to overview the different existing virtual systems and applications involving the use of virtual reality for ULA patients.

2.1 Virtual reality and upper limb prostheses

As introduced in the **Section 1.4**, the complexity of myoelectric prostheses is one of the reasons why we find a high rate of rejection in many ULA patients and even abandonment of prostheses [5]. This can be explained by the long training phase during the **rehabilitation process** (**Figure 2.1**) following the prescription of the prosthesis which can be very exhausting for the patient.

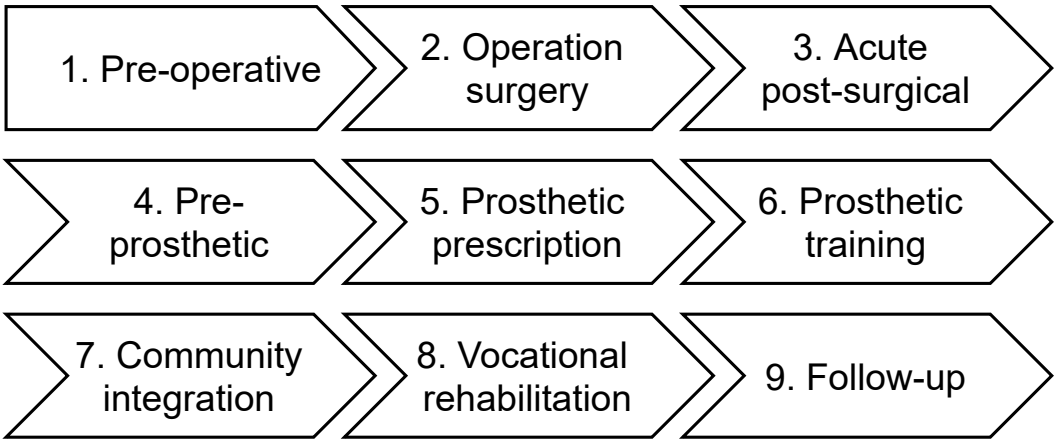


Figure 2.1: The 9 phases of rehabilitation for an amputee patient according to Esquenazi A. Adapted from [2, 3].

Therefore, virtual systems have been developed by prosthesis manufacturers, with the help of researchers, to facilitate the process and avoid rejections. With these virtual systems, the learning of the prosthesis as well as its evaluation for the clinician and the prosthetist can be facilitated. In order to train patients to use a myoelectric prosthesis, most of the available virtual systems are based on a simple **EMG biofeedback** (BFB). It is useful for learning the basic functions of the prosthesis, i.e generation of muscle

activity. However, this does not allow a deeper understanding of the prosthesis itself. The following sections of this chapter will therefore focus in more depth on the different types of virtual systems that exist, particularly in the field of rehabilitation.

2.2 Available virtual rehabilitation systems

2.2.1 Type of virtual systems

Three types of virtual systems, in addition to EMG biofeedback, have been highlighted by Dawson in one of these reviews [41]: serious games, 2D and 3D simulators. The first virtual system, namely serious games controlled by EMG signals, is intended to help train ULA patients by focusing on a playful component. Although, the complex movement patterns of myoelectric prostheses are missing as well as EMG biofeedback. As a result, several 2D and 3D simulators have been developed, in order to simulate these complexities and allow the interaction between the user and the prosthesis via EMG signals. However, the Dawson's review was limited to the search for virtual training systems to facilitate the process. Yet, the selection of the right prosthesis is an equally important element in the rehabilitation process in order to avoid any rejection.

Last year, a systematic review of the field of application was conducted by Mr. Hugo Ghazi, Prof. Renaud Ronsse and Mr. Alexis Lheureux [42]. One of their objectives was to discover most of the existing virtual systems for the rehabilitation of upper limb amputations. A discussion on the advantages and disadvantages of these virtual tools was performed.

Firstly, this review has shown that a large majority (98%) of the virtual systems designed in these studies (n=54) had a purely formative purpose, followed by a research purpose (56%) and an evaluative purpose (33%) but that no applications were developed for prosthesis selection. Secondly, in most of the studies that have been conducted, a large majority (54%) used a 3D simulator as the virtual system. However, we will see that there are many other alternatives.

Figure 2.2: "General view of the UNB Universal Myoelectric trainer" [43].

In the review, the earliest paper that was found (Lovely, 1988, *University of New Brunswick* [43]) used an EMG control device (**Figure 2.2**) to evaluate and train myoelectric prostheses. The method used, which consisted of a BFB EMG, is still used today in clinical practice and for commercially available virtual systems, notably from prosthesis manufacturers such as *Ossür* and *Ottobock*.

Table 2.1 shows the different virtual systems found for *Ottobock*, *Ossür* and *UtahArm*.

Virtual systems	Company	Description
"MyoBoy"	Ottobock	Designed for clinicians and prosthetists for training and evaluation of EMG BFB control
"Bebalance" (almost the same as "MyoBoy")	Ottobock	Designed for the user for training and evaluation of the BFB EMG control as well as for the personalization of the Bebionic prosthesis
"Paula 1.2"	Ottobock	Designed for the design of the sockets
"BioSim"	Ossür	Designed for the user to edit and customize the i-Limb prosthesis and to perform EMG control tests
"Myolab II"	UtahArm	Designed as a BFB EMG for training and evaluation purposes

Table 2.1: Different virtual systems found for *Ottobock* [44, 45, 46], *Ossür* [47] and *UtahArm* [48].

Although simplistic virtual systems involving an EMG BFB system are mostly used by manufacturers for training and evaluation purposes, 3D simulators can be much more effective. Indeed, the immersion allowing direct interaction with the prosthesis without even wearing it could accentuate the involvement of the user and the learning process of this type of tool. Resulting in an increase in the users' satisfaction with their prosthesis.

2.2.2 Type of display

Concerning the type of display, the review reveals that only 15% of the studies (n=8) used virtual reality as a visualization method compared to 85% (n=47) that used a 2D display.

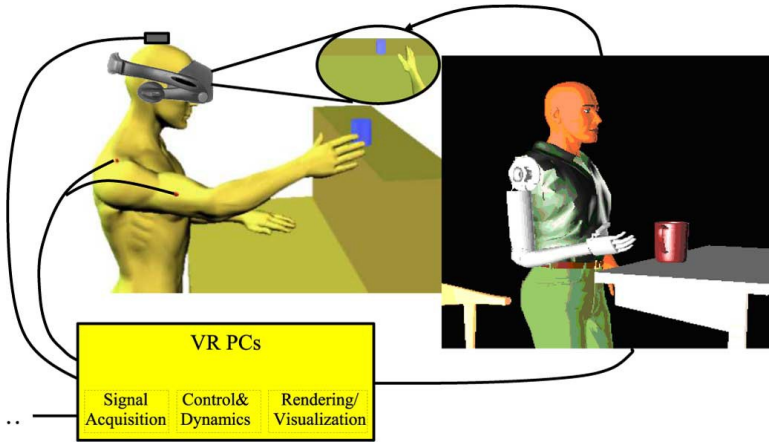


Figure 2.3: "In the VRE, subjects can operate a simulated prosthetic arm to interact with virtual objects. Multiple input modalities such as motion tracking systems and EMG/EEG electrodes provide maximum flexibility when evaluating different control approaches. Figure shows a subject operating a prosthetic arm prototype in VR (right side). Subject controls the arm via real-time motion tracking (left side), and 3-D visual feedback is provided via stereoscopic goggles for closed loop operation" [49].

It was not until 2007 that the first study using virtual reality in a rehabilitation aid for ULA prostheses appeared. This study was conducted by Hauschild [49] (**Figure 2.3**). As for the other studies, they were conducted after 2010, i.e the year when VR became more and more popular thanks to the use of a head-mounted display with the prototyping of the *Oculus Rift* [50], but remain very few. This may be justified by the fact that virtual reality is still a developing technology, its expansion into the field of medicine and rehabilitation is still quite small, and it is often defined, incorrectly, as any human-computer interaction [51].

2.2.3 Virtual systems setup

Two types of virtual system configurations are most commonly used in the studies found in the review: a conventional controller with 2 channels of electrodes and a pattern recognition controller with 8 channels of electrodes. Even though, some studies have used 12 or even 15 channels.

The first configuration, namely conventional controller, generally allows to model a type of movement, mainly the opening, controlled by one electrode, and the closing of the hand, controlled by the other electrode. Moreover, the speed and the force of movements, are both proportional to the amplitude of the EMG signal [52]. It is very often this configuration, considered simpler to use and to control, that we find in most of the prostheses already on the market, i.e *Bebionic*. The second configuration, namely pattern recognition controller, which aims to reproduce a more natural movement pattern, uses several EMG channels to exploit a greater number of different muscle sites. In addition, a classifier is used to categorize and process the different information received in order to decide on the desired movement pattern using a specific algorithm.

2.2.4 Clinical trials

Clinical trials can be used to evaluate the effectiveness of a tool for the purpose of training and evaluating the ability of an amputee to use a prosthesis. Although, among all the studies that conducted a *"Design and Development"* with or without a preliminary experimentation, very few (13%) led to clinical trials.

In most cases, the development of the tool and the trial were carried out at the same time, except for two studies carried out by Prahm [53][54]. Through these 2 studies, Prahm had 2 precise objectives: the realization of a new tool based on serious games (**Section 2.3.1**) as well as the evaluation of its effectiveness through preliminary experiments, i.e case studies with a total of 18 patients - 7 amputees and 11 able-bodied.

2.3 Serious Games existing

This section aims to review some clinical studies to highlight existing serious games.

2.3.1 Prahm study

During Prahm's study, three serious games were used by the participants (**Figures 2.4, 2.5 and 2.6**).

Figure 2.4: Racing Game (*Super TuxKart*) [53].

The first game was a racing game called *Super TuxKart* (**Figure 2.4**). The vehicule was control using two input methods: "EMG" and "Non-EMG hand". The first method allowed to control its directions, i.e turn right or left. This could be done thanks to two types of contractions: "quick contractions" and "prolonged contractions". While the second method allowed to control its speed, i.e acceleration and braking.

The second game was a rhythm game called *Step Mania 5* (**Figure 2.5**). The principle of the game consisted in the activation of directional arrows via 2 input methods: "EMG" and "Cocontraction". The first method allowed the activation of the left and right arrows separately, thanks to a "quick contraction" and a "prolonged contraction". While the second method allowed the activation of both arrows simultaneously, thanks to a simultaneous contraction of the flexor and extensor muscle.

Figure 2.5: Rhythm Game (*Step Mania 5*) [53]

Figure 2.6: Dexterity Game (*Pospos*) [53].

The last game was a dexterity game called *Pospos* (**Figure 2.6**). The control of the game was also done with 2 input methods: "EMG" and "Cocontraction". The first method allowed a directional control, i.e moving left, right, up and down, through a "quick contraction" and a "prolonged contraction". While the second method allowed to change the axis of control between left/right and up/down through a simultaneous contraction of the flexor and extensor muscle.

2.3.2 Nissler study

Among the different studies simulating only an opening and closing movement of the prosthesis, the Nissler's one [55] has been considered the most advanced. There is 2 main features. On one hand, a coupling between a pattern recognition and 8 EMG electrodes to control up to 4 grip patterns for the hand, namely relaxed, fist, pointing and pinching, to accomplish a task. In the other hand, a proportional control of the

grip force according to the amplitude of the emitted EMG signal for a more precise control of the movement (**Figure 2.7**). However, even if this study certainly allows better use of a prosthesis, it has no impact on the choice of a prosthesis.

Figure 2.7: Nissler study - Illustration of the proportional control of the grip force according to the amplitude of the EMG signal. The increase of the force implies a deformation of the pig's eyes [55].

To conclude, this state of the art gives an overview of existing devices mixing upper limb prosthesis and VR. There are indeed tools that have been developed to improve the rehabilitation process of ULA people using serious gaming. Although, it also shows that very few, if any, studies have so far developed a virtual tool allowing to have a crucial role in the selection of myoelectric prosthesis using virtual reality as display. It means that the work done for this project is a **pioneer** in its field and, as far as we know, no other works have developed this idea yet.

Chapter 3

Methods

This chapter aims to provide instructions for use of the work that has been done during this thesis. It is following a *top down* outline, i.e from a really wide point of view to a very detailed one. It begins with a description of experimental trials, explaining the process used to test the subjects. Secondly, the global environment is detailed. Then, the data collection and analysis is given. A last section explains the fully detailed system architecture and operation.

3.1 Experimental trials

This section gives a description of the experimental campaign that was conducted for this work. It reviews the evaluation methods and the experiment protocol that were designed.

3.1.1 Evaluation methods

In order to test our **hypotheses**, it is needed to observe quantitative and subjective outcome of the subject. Hence, the evaluation of the subjects was done in two different ways.

On one hand, **surveys** were proposed to assess the subject's opinion about the prostheses and to evaluate the "virtual" usability of each prosthesis. The opinion questionnaire aims to see if testing prosthesis in VR change or consolidate the subject's vision towards which prostheses they prefer. Thus, we used a **before/after VR** survey based on the one designed in last year's thesis. Concerning the usability aspect, a survey on the **system usability scale** (SUS) has been used. The full description of the data collected in these survey is described in **Section 3.3**.

On the other hand, the second evaluation method consists in the realization of **virtual tasks**. Several tasks had to be performed with each prosthesis by the subjects. These tasks provide source of quantitative data, such as time or co-contraction. All the tasks' instructions can be found in **Appendix D**, they were the following:

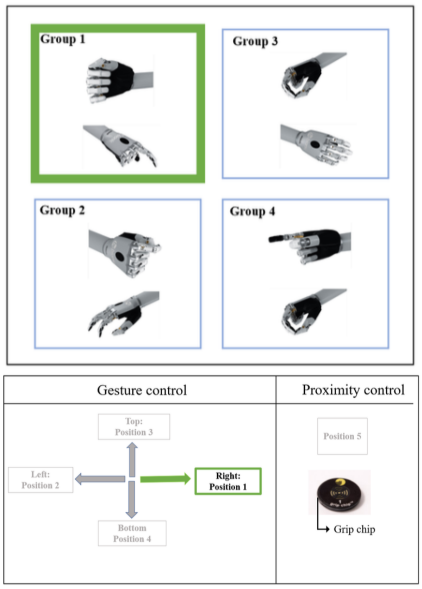


Figure 3.1: Interactive panel for *Bebionic* (top) and *i-Limb* (bottom).

Task 2 (a&b): Manipulating blocks.

Firstly, the participants were required to interact with virtual blocks that were installed on a virtual desk. The goal was to construct a castle out of six different sized and shaped blocks, as shown in **Figure 3.2**. The good grip pattern had to be enabled in order to complete this construction (**Figure 3.3**).
Then, after the castle was completed, the subjects were instructed to shift the smallest cube without crushing the whole structure. The participants had to switch grip patterns with *i-Limb* and *Bebionic* and choose the one with the pointing index finger. With *Greifer*, the subjects had to drop the small cube.

Task 1: Exploring the prosthesis control (Only for *Bebionic* and *i-Limb*).

The subjects had to imitate the hand position shown on the slide. *Greifer* was unconcerned because there was no grip adjustment to assess. The participants were given clear instructions about how to modify their grip patterns. A "Congratulations" flag emerged after the subjects had successfully accomplished a grip pattern. An interactive panel (**Figure 3.1**), on the back was displayed with the current group/grip pattern triggered by the prosthesis to prevent participants from being lost.

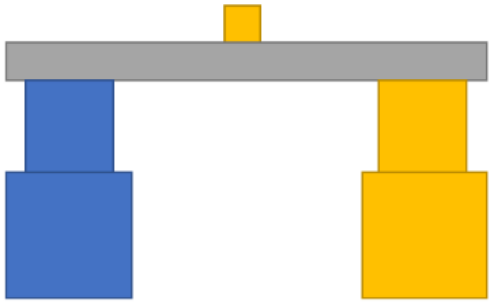


Figure 3.2: Castle made of blocks.

3.1.2 Experiment protocol

An overview of the experiment is shown in **Figure 3.4**, followed by a detailed explanation of each step. The experiment was performed in **three sessions over two weeks**. The required time to perform each session was about one hour.

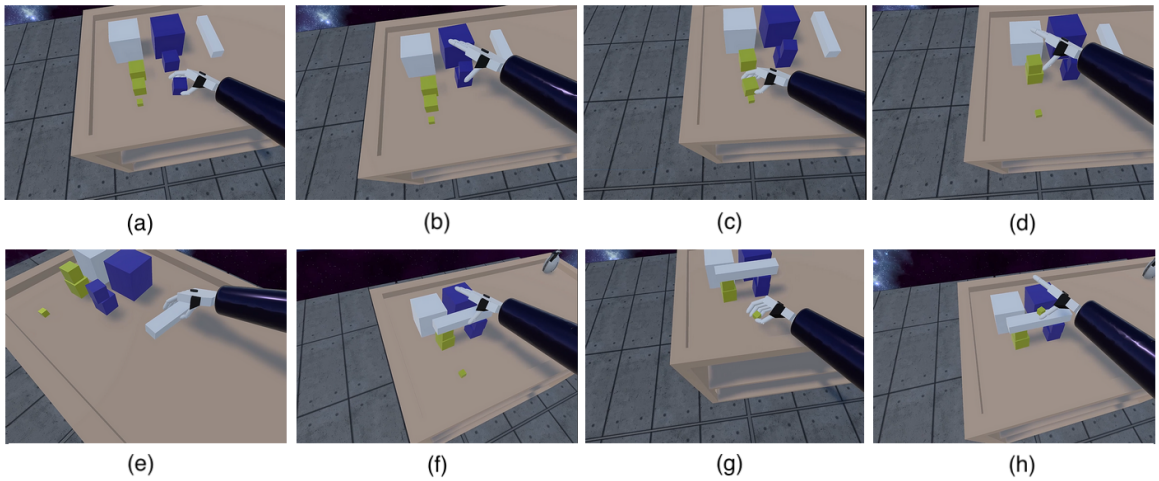


Figure 3.3: Screenshot from a successfully trial on task 2 showing the subject building the block castle with Bebionic prosthesis. The screenshot correspond to the visual feedback given by the HTV Vive Headset to the subject during the tasks in the VR experiment.

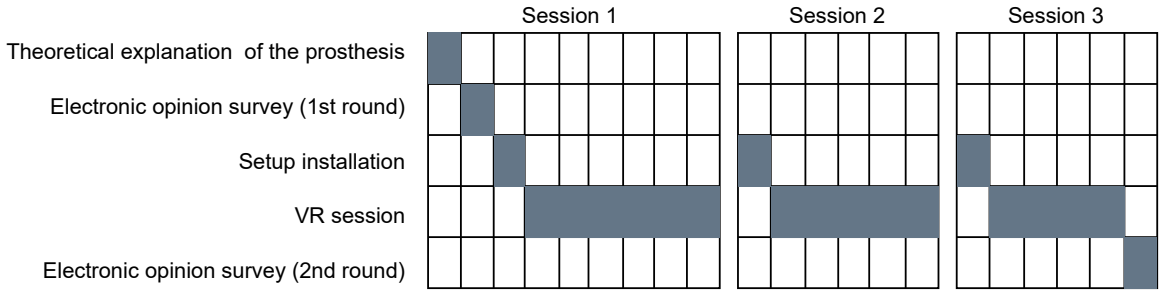


Figure 3.4: The experimental timeline. Experiment was performed in 3 sessions over two weeks. Opinion surveys were completed before session 1 and after session 3. Each box in the timeline corresponds to approximately 10 minutes.

Theoretical explanation

During the first session, a brief presentation of the experiment is made to allow the subjects to clearly understand the objective of the experiment. During this presentation, the general context in which ULA patients have to choose their future prosthesis is explained.

Afterwards, a theoretical explanation of the three prostheses is performed in order to simulate the presentation of the prostheses made by the manufacturers to the ULA patients. Each prosthesis is explained orally with the support of a video made directly by the manufacturer.

Electronic opinion survey: First round

After getting a first impression of the prostheses, an opinion survey is filled out for the first time by the subjects.

Setup installation

During each session, the installation of the configuration is carried out. First, the **portable hardware** is fixed on the subject's biceps. Then, the EMG electrodes are placed on the forearm and the Vive tracker is placed above them, around the forearm, thanks to an adjustable cuff.

Once in the virutal reality, each subject is given an explanation of the two **movements required** (hand flexion and extension) to activate each electrode (**Figure 3.5**).

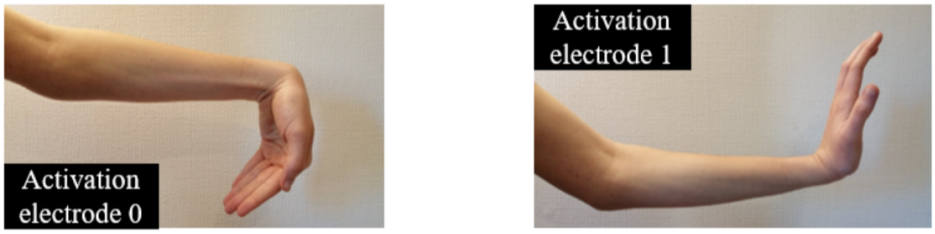


Figure 3.5: The two movements performed by the subjects. Flexion (resp. extension) of the hand to activate electrode 0 (resp. 1) [42].

Then, the **threshold adjustment** is performed. The thresholds were set one at a time. After a few repetitions of each movement, the thresholds were correctly adjusted. The electrode gauges were visible to the subjects. Subjects were able to see how their own muscle contractions affected the signal amplitude thanks to this visual feedback. It was critical to devote some time to allowing the subject to become acquainted with the surroundings and signals. The threshold adjustment was critical because if the two thresholds were not perfectly adjusted, the participants would struggle to complete the tasks correctly.

VR session

The VR session is divided into 4 steps (**Figure 3.6**).

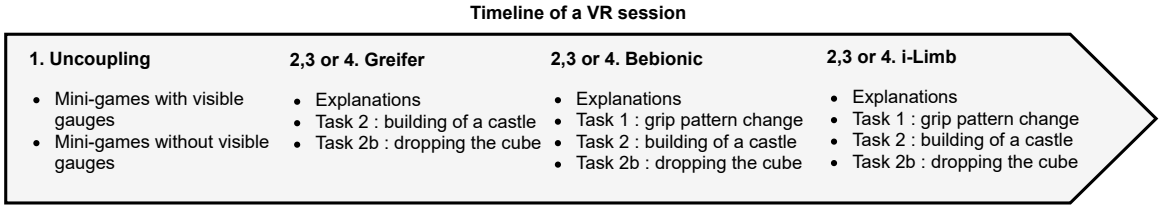


Figure 3.6: The virtual reality tasks timeline. Subjects start with uncoupling activities and then test the 3 implemented prosthesis. The order of testing the prosthesis is randomised.

Firstly, before trying the different prostheses, the subjects are brought to test 3 **mini-games** using only the EMG signals. This set of activity was not implemented in last year's thesis and aims to fully isolate and implement the **learnability** of the interface. Hence, when the subjects test the prostheses, we assume to be able to measure usability/learnability of the prosthesis itself. Performing these mini-games,

both with and without visible EMG gauges, allows subjects to become familiar with the environment and the signals.

Once the familiarization stage is over, the testing of the different prostheses can begin. For convenience, all subjects started the first session with *Greifer*, considering that it was the easiest one to become familiar with the opening/closing system. However, for the rest of the first session and the other sessions, the order of tested prostheses has been **randomized**.

Each prosthesis is tested one after the other. The procedure is similar for the 3 prostheses.

- First, the **selection of the prosthesis** is done.
- Then, the subject is immersed in the **testing room**. A few slides are displayed in the background of the scene so that the subjects can read while the examiners give oral explanations.
- The **first task** (only for *Bebionic* and *i-Limb*) is to review each grip pattern implemented for the prosthesis.
- The **second task** is to build a castle with cubes of different sizes. Once the castle is built, the subject must change the grip pattern in order to have a pointing index finger to push the smallest cube to the top of the castle.

Electronic opinion survey: Second round

After the third session, two opinion surveys are asked to be filled in at the end of the VR immersion. The first one corresponds exactly to the one before the immersion in VR of the first session and the second one concerns the usability scale of the system.

3.2 Global environment

3.2.1 Study design

The experimental campaign, which was designed for this thesis, is a case series study. In order to ensure the completeness of the items to be included in the observational studies, we used the *STROBE checklist* [56, 57].

3.2.2 Settings

The experiment was conducted in the *Institute of Information and Communication Technologies, Electronics and Applied Mathematics* (ICTEAM in Louvain-La-Neuve, Belgium) between Mars 8 and May 7, 2020. Before starting the main experiment, a validation trial on 2 able-bodied subjects took place between February 15 to 24.

The first round of experiment (Mars 8 to April 2) only focused on the able-bodied participants while the second round (April 19 to May 7) included able-bodied and an ULA participant. **Appendix B** is a *Gantt Chart* of the project. It overviews the

different experimentation periods.

The recruitment for able-bodied subjects was done gradually during the experimental period through social network by the researchers. For the ULA participant, *Amptraide*[1] announced the project in November and solicited expressions of interest from ULA patients. However, there was little feedback from potential ULA subjects during the first round of testing. A second announcement was therefore made in early April.

Regarding the data collection, data was initially stored on an *Excel* file and on *Microsoft* Form. Later on, the data was transfered to the *UCL* servers. This aspect is more detailed in **Section 3.3**.

3.2.3 Study population

This study is a proof of concept in which **12 able-bodied** subjects as well as **1 ULA** patients voluntarily participated. Due to the sanitary crisis, the able-bodied subjects were recruited only from *Université Catholique de Louvain*.

The following criteria were used to perform inclusion/exclusion of able-bodied test subjects:

- **Inclusion criteria:** Able-bodied subjects, between 18-40 years old, fluent in French.

  This experiment focused, during its first round, on able-bodied subjects. Indeed, it is easier to recruit able-bodied subjects as upper limb amputee population is considered very low. For age range, it was set in between 18 to 40 years old as most upper limb amputations are caused by traumatic injuries, such as high velocity auto accidents and workplace injuries, which mostly happen in younger age (**Section 1.1**). Concerning the language, subjects needed to be fluent in French as the intervention directives and evaluation questionnaires were in French.

- **Exclusion criteria:** Any impairment and any previous experience with EMG control.

  Subjects with any impairment and any experience with EMG control were excluded to avoid a risk of bias and possible effect on outcomes.

Regarding ULA patient, no exclusion criteria were used because of the difficulty to recruit subjects. As long as they had a transradial amputation with a sufficient residual limb length, they could be included in the experiment. All participants provided their written *informed consent* (**Appendix C**) for the collection and use of their data.

3.2.4 Closed-loop control

The system follows a **closed-loop** control similar to a real **bionic** prosthesis. Indeed, an actuation pathway and the visual feedback loops can be defined in the case of a virtual prosthesis, as shown in **Figure 3.7**.

[1] An association mainly composed of amputees or people with limb agenesis.

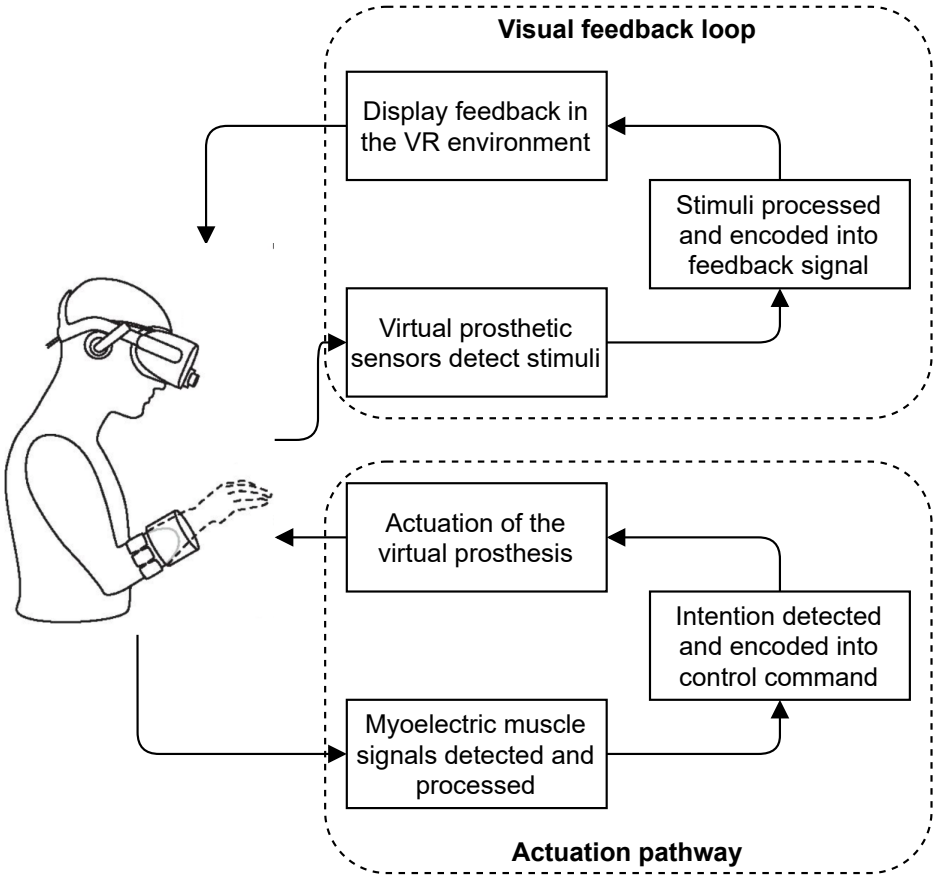


Figure 3.7: Closed-loop control for a virtual bionic prosthesis. The myoelectric data acquisition is done by 2 EMG electrodes to estimate the user motion intention and command the virtual prosthesis. The subject can attend the actuation of the prosthesis and interact with the virtual environment thanks to a visual and audio feedback. Adapted from [58].

The **actuation pathway** consists of the acquisition of the myoelectric signals from the patient. These signals are translated into an intention that is encoded into the control command leading to actuation of the prosthesis. This loop allows the open/closing of the prosthesis as well as the change in grip patterns. The **visual feedback loop** consists of the detection of the stimuli from virtual objects. These signals are processed in the software and encoded into a feedback signal that is displayed in the VR environment. For example, this loop corresponds to the successful or unsuccessful grasp of a cube that provides a visual feedback to the subject.

3.3 Data collection and analysis

This section reviews all the data collected during the experiment protocol. It gives the variables, the data sources and measurement for both quantitative and subjective data. Then, a brief description of the **Data Managment Plan** (DMP) is done. Eventually, the study size and statistical methods used in this work are explained.

3.3.1 Variables

Outcomes There are 3 main dependent variables in this study: the participants' subjective opinion on each prosthesis, the time to complete each task and the number of co-contractions performed at the end of each task.

Exposure As for the exposure variable, only 2 were considered: the detailed explanation of the prosthesis characteristics and the VR session. This is justified by the fact that we consider, by hypothesis, that these 2 variables influence the subjective opinion.

Potential effect modifiers and/or confounders Finally, 2 potential confounders can also be considered in this study: the fidelity of the immersion (due to a non-perfect reproduction of the real prosthesis) and the selection of the participants (which was restricted due to the Covid-19 pandemic)

3.3.2 Data sources and measurement

Quantitative variables

During the exploration of the prothesis's control, i.e task 1 and the manipulation of the blocks, i.e task 2, the data measured were the **time** and number of **co-contractions** at the end of each task. The measurement has been performed during the 3 VR sessions for each prosthesis in order to analyse the data as a learning curve along all the experimental campaign procedure.

Subjective variables

As introduced in the evaluation method (**Section 3.1.1**), 2 types of survey were used during the experimental campaign, namely the **SUS** (**Appendix E.1**) and the **before/after VR testing** surveys (**Appendix E.2**).

System Usability Scale (SUS):

In 1986, John Brooke created the "System Usability Scale" in an effort to meet a rapid need for an electronic system. This questionnaire is a reliable and "*quick and dirty*" tool to measure usability. It consists of a 10-questions questionnaire that collects the user's subjective view on a system or service. It is based on a scale that allows the user to answer on a scale from "strongly disagree" to "strongly agree". It has many advantages including being an easy scale to administer to participants, reliable results even for small sample sizes, and its validity due to its ability to differentiate usable and non-usable systems.

Once the user has answered all the questions, a unique number is given, allowing to represent a composite measure of the global usability of the studied system [59]. Its calculation is quite particular and is presented as follows:

- For odd-numbered items, the score is the result on the scale minus 1.
- For even-numbered items, the score is 5 minus the result on the scale.

- All score are added and then the result is multiplied by 2.5 to obtain the SUS score which varies from 0 to 100.
- Finally, the scores of the participants are averaged.

It is important to specify that although we obtain a score from 0 to 100, the SUS score does not represent a "usability percentage".

Before/after VR testing:

Concerning the before/after VR questionnaire, a grouping in different categories can be made for the questions (**Table 3.1**).

Question category	Collected data
Personal information	Age, Profession, Handedness (Left/Right handed)
Prostheses classification according to general criteria (Q3-Q14)	Classification of the 3 prostheses between them according to specific criteria (aesthetics, functionality, robustness, intuitiveness, innovation, motivation to learn). *Note: In order to ensure that the subjects do not answer randomly, a duplication of each question has been realized.*
Activity-based questions (Q15-Q17)	Selection, for each of the 3 prostheses, of the activities with which the subjects would be comfortable to carry out, from a non-exhaustive list of 8 activities (eating, dressing, using a telephone, shopping, cooking, cleaning and maintaining a house, doing laundry and moving around (bicycle, car...))
Final question (Q18)	Final choice of preference among the 3 prostheses.
Impact of VR (Q19)	Opinion on whether or not virtual reality had an influence on their choice of prosthesis *Note: This question is only asked in the second questionnaire*

Table 3.1: Grouping the question of the opinion survey in different categories

Bias

A potential source of bias could come from the material used or subject tested:

- If the batteries were not well charged, some bugs might occur and influence the time measured on tasks.
- The value of the thresholds will have a great influence on the number of cocontractions measured. In order to limit this bias, we tried to keep the same thresholds for the 3 sessions of the same subject. However, sometimes subjects would not feel comfortable anymore with their previous session's threshold and it might be needed to change them.
- The level of experience of the ULA patient with the EMG signals and the different prostheses implemented will imply a significant bias.

Data Management Plan

A DMP is a formalized document that explains how we decide to obtain, document, analyze, disseminate and use the different data that will be produced during our thesis. The choices are described in terms of metadata[2] standards, database formats, access methods and security of access, archiving times, as well as the costs associated with the management of the data. Therefore, its goal is to document how data is produced or collected, during and after our work process, and how it will be described, shared, protected and preserved.

The realization of a DMP is very important since our data are considered as unique and valuable resources. Hence, it is necessary to manage them in a correct way to ensure for the future a good accessibility, comprehensibility and reusability of the same data. The DMP done for this work can be seen in **Appendix F**.

3.3.3 Study size

Before starting the experimental campaign, a validation of the protocol have been done on 2 subjects. Based on their data, a **power analysis** for a bifactorial **Analysis Of Variance** (ANOVA), using F-test, was performed to estimate the minimal sample size needed to detect a significant main effect for one of the factors or to detect a significant interaction. In this experiment, the free variable will be either the time required to perform the task or the occurrence of co-contractions during the task. The 2 factors will be the sessions and the prosthesis used.

First, we have to determine the effect size based on the partial η^2, which is the total variance in the outcome variable (time or co-contraction's occurrence) accounted for by a factor or interaction between factors. Then, we select a Type 1 (α) error rate, usually 0.05 and a level of statistical power, usually 0.80. We still need to evaluate df, i.e the number of levels for the factor variable or interaction minus 1 and the number of groups, i.e obtain by multiplying the numbers of levels in both factors variables. Based on all those inputs, we can compute the non-centrality parameter λ, the critical F and eventually the **total sample size**.

To facilitate the calculations, the power calculator *G*POWER* was used. The methodology previously described need to be carried out for each task, for both free variables (time and co-contraction's occurrence) and each factor and their interaction. A summary of the inputs, intermediate results and outputs can be found in the **Appendix G.1**.

The largest sample size computed should be chosen for the experimental campaign. However, it is observed in the **Tables G.1 and G.2**, that some values are not feasible in this work. A compromise was therefore made and a sample size of about **13 participants** was targeted.

[2]Metadata is data that describes other physical or digital data and resources. (e.g. geolocation or date and time on a photo, number of pages on a document)

3.3.4 Statistical methods

In order to determine if the number of sessions, the type of prosthesis or the combination of both had a real impact on the time and the number of co-contractions, a bifactorial ANOVA was carried out. For ease of use, the computation has been done with *SPSS statistics* but the methodology to obtain the results is described in this section.

The continuous variable to be explained, x_{ijk}, will be either the time or the number of co-contractions and the 2 factors of variability that were chosen are the **number of sessions** (that can take the levels $j = 1, 2, 3$) and the **type of prosthesis** (levels $k = 1, 2, 3$).

The ANOVA model used in this study is the following:

$$x_{ijk} = \mu + a_j + \beta_k + a\beta_{jk} + e_{ijk}$$

in which:

- x_{ijk}**:** the qualitative variable to be explained (the time/number of cocontractions)
- μ**:** overall average (constant)
- a_j**:** the effect of level j of the first factor - the number of sessions (cancels out if the first factor has no effect)
- b_k**:** the effect of level k of the second factor - the type of prosthesis (cancels if the second factor has no effect)
- $a\beta_{jk}$**:** the effect of the interaction of levels j and k (cancels if there is no interaction effect between the 2 factors)
- e_{ijk}**:** the random error (following a normal distribution)

Before being able to apply ANOVA, certain **conditions** had to be respected, i.e the normality of the distribution (verified by hypothesis) as well as the independence of the samples (verified by the problem).

The **3 hypotheses** tested are summarized in **Table 3.2**:

H0	There is no main effect of the first factor, i.e the number of sessions.
H1	Two-sided: there is a main effect of the first factor
H0	There is no main effect of the second factor, i.e the type of prosthesis.
H1	Two-sided: there is a main effect of the second factor.
H0	There is no interaction between the 2 factors.
H1	Two-sided: there is an interaction between the 2 factors.

Table 3.2: Different hypotheses tested in the multifacorial ANOVA

In order to calculate these different variances, we use the **Sum of Squares** (SS), the **Degrees of Freedom** (DoF) and the **Mean Squares** (MS). Details about the

calculation of SS, DoF and MS can be found in the **Appendix G.2**.

Once the all MS have been calculated, the calculation of the test statistic can be done. Under H_0, the 3 ratios of the mean squares A (i.e first factor), B (i.e second factor) and A*B (i.e interaction between both factor) with the mean square within (W) are distributed according to a **Fisher-Snedecor F distribution**:

$$F_{(DoF_A, DoF_W)_{obs}} = \frac{MS_A}{MS_{within}}, F_{(DoF_B, DoF_W)_{obs}} = \frac{MS_B}{MS_{within}}, F_{(DoF_{A*B}, DoF_W)_{obs}} = \frac{MS_{A*B}}{MS_{within}}$$

- **If F = 1:** there is no effect of the first or second factor or of the interaction between the two.
- **If F > 1:** in this case, the statistical test will specify according to the level of significance (e.g. $p = 5\%$), up to which an excess of 1 is acceptable (above: H_0 will be rejected in favor of H_1 and vice versa).

In the case of using *SPSS statistics*, a value for significance is directly provided. If this value is lower than the level of significance, the null hypothesis H_0 is **rejected**.

3.4 System architecture and operation

This section gives a detailed description of the prototype used during the experiment. It is divided in 5 parts. It begins with the experimental conditions. Secondly, an overview of the system, reviewing the muscle computer interface and the VR hardware. Then, the virtual environment built with *Unity* is presented. The implementation of the learnability of the user interface is shown afterwards. A last section explains how the prostheses were implemented virtually.

The system architecture was mainly designed during last year's thesis. However, some improvements have been made to better match the experimental protocol designed this year. They are described in this section.

3.4.1 Experimental conditions

The experiment was performed in a VR laboratory (**Figure 3.8**). The latter is an roughly empty room equipped with a table in its center. Since the hardware barely limits the movements, the participant is free to move in the environment around the table. The needed experimental hardware (detailed in **Section 3.4**) consisted of a **HTC Vive head-mounted display** (HMD), **Vive tracker**, **Vive controller** and four **base stations**. It also required an high-end computer and finally an in-house built EMG controller composed of *MyoWare*^{TM} electrodes coupled with an *Arduino Uno* micro-controller. The computer used was an *Alienware* provided by the laboratory, placed on the central table.

The localisation of the VR devices was ensure by the 4 base stations. They were placed in each corner of the room, allowing the smoothness of the localisation whatever

the position of the subject. The base stations' height is roughly 3 meters and they have to be angled down by 30-45 degrees.

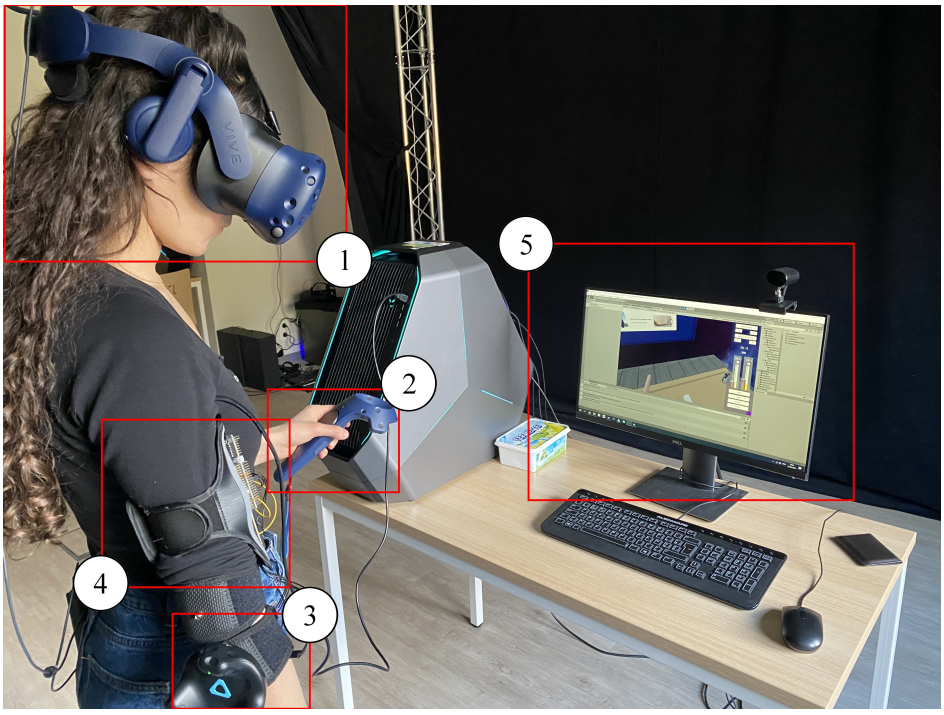


Figure 3.8: Overview of the setup: (1) HTV Vive HMD, (2) HTC Vive Controller, (3) *MyoWare*^{TM} electrode covered by HTC Vive Tracker, (4) Muscle Computer Interface, (5) Computer and (6) Base stations (not visible in this picture).

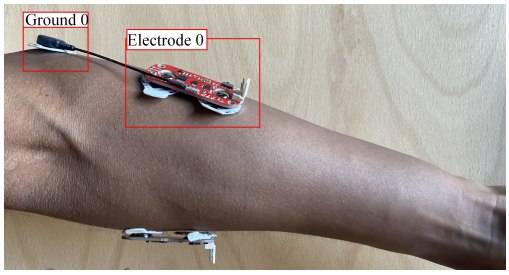
Compared to the prototype used in last year's thesis, all the hardware required has been made portable. This improvement allows the subject to perform the different tasks without having to sit in front of the computer in order to really enjoy the sense of presence offered by VR (**Section 1.3**). Moreover, before this improvement, the examiners had to pay attention that the subjects did not do too sudden movements which could induce loss of connections in the wires of muscle computer interface.

Electrode placement

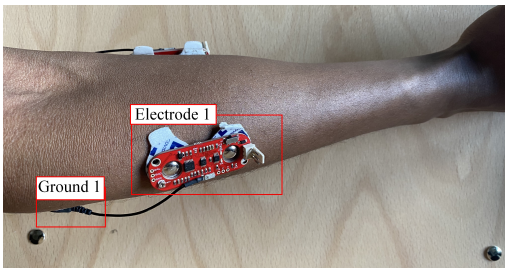
Before placing the electrodes on the arm, it was important to clean the zones with a hydroalcoholic solution. One bipolar EMG electrode was placed on the wrist extensors, while the other was placed on the wrist flexors as shown in **Figure 3.9**. Furthermore, the reference electrodes were put on the humeral bone's medial and lateral epicondyles, respectively.

Since electrode placement is unique to each patient, there is no common position for electrode placement. Bipolar surface sensors should be located somewhere in an arbitrary line between two anatomical muscle landmarks, according to *SENIAM* guidelines [60]. The appearance of motor points, muscle tendons, and other active muscles near the EMG sensors are all indicators of a good location. To find a successful and reliable EMG along this imaginary axis, a "trial and error" technique was used. To reduce

the possibility of interference with the bipolar electrode positioned on the muscle, the reference electrode should be placed on an electrically inactive tissue such as a bone.



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



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

Figure 3.9: Placement of the two electrodes on the right forearm of a subject.

3.4.2 Overview of the system

An overview of the system architecture is visualised in **Figure 3.10**. During the whole process, the myoelectric signals of the subject are collected by 2 EMG electrodes *MyoWare*^{TM}. These electrodes transmit an EMG envelope to an *Arduino Uno* micro-controller. The latter is a circuit board with a micro-controller. It provides the collected data as a 32bit digital message to the computer where it is treated inside *Unity* software to control the virtual prosthesis.

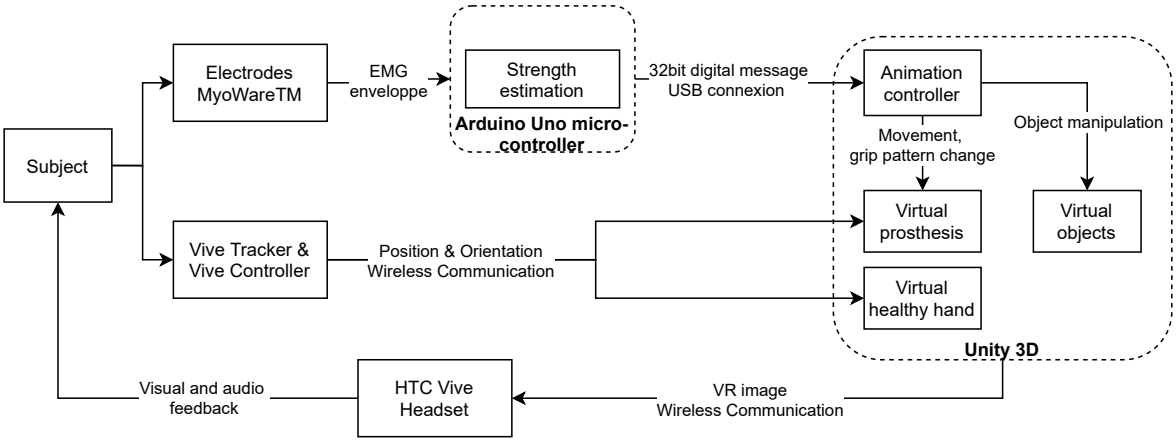


Figure 3.10: Overview of the system architecture with main components and data flow: an *Arduino Uno* micro-controller is used to process the myolectric signals from the electrodes *MyoWare*^{TM} and the animation controller[3]ensures the opening and closing of the prosthesis as well as the changing of available grip patterns. Localisation of the virtual prosthesis and healthy hand by Vive Tracker and Controller. A visual and audio feedback of the treated data is provided by the HTC Vive Headset. Details are in the text.

[3]An Animaton Controller is a Unity asset that controls the logic of an animated GameObject

The system also requires to have the position and orientation of the virtual prosthesis and the healthy hand. This is given by wireless communication from two tracking joysticks, i.e the Vive Tracker for the prosthesis and the Vive controller for the healthy hand. This device aims to virtually try transradial bionic prosthesis, hence the Vive Tracker is placed on the forearm near the elbow, at the end of the imaginary residual limb.

Based on the myoelectric signals and the tracking devices' location sent to *Unity* software, a visual feedback is displayed in the VR environment. Eventually, the HTC Vive headset provides the visual and audio feedback to the subject.

Muscle computer interface

The experimental setup used in this work was designed in last year thesis. The board is displayed in **Figure 3.11**. Due to a problem of loss of contact between the cables and the board because of too abrupt movements of the participants, some improvements have been made.

First, the board was replaced by a prototype board allowing to weld the cables directly instead of just having them pushed in. Then, in order to allow the participants to be as free of their movements as possible, the setup was fixed on a running armband. This armband can easily be attached around the biceps of the participants and does not require them to sit still in front of the table like in the first version of this setup. The picture of the real setup used can be found in **Appendix H.1**.

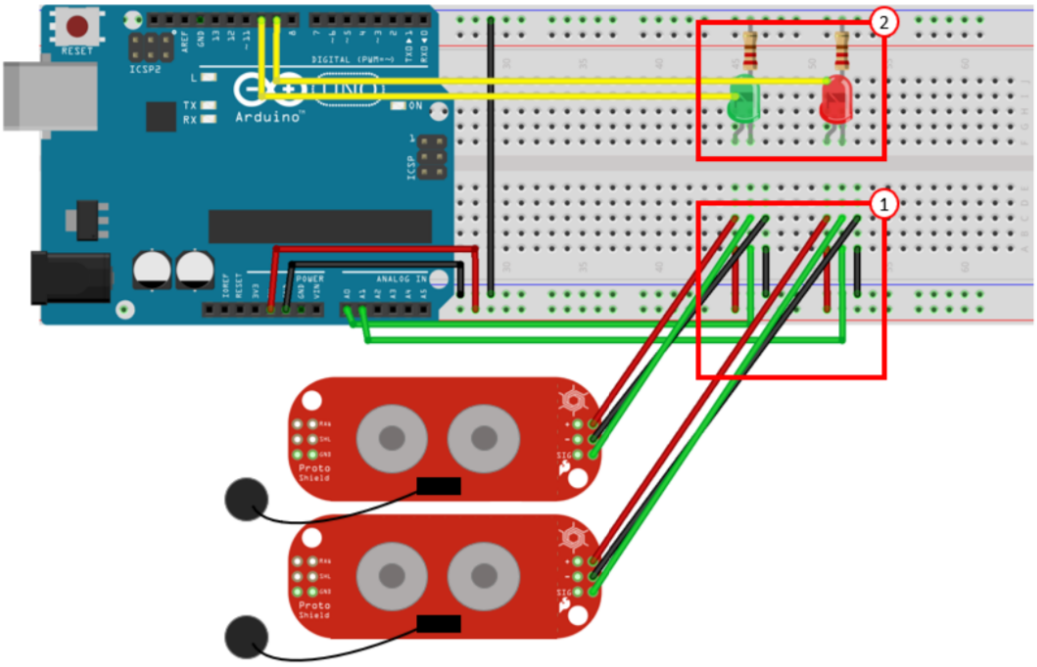


Figure 3.11: Illustration of the cleaned setup made last year [42]. (1) Electrode interface, (2) Feedback LEDs. Drawn with Fritzing Software.

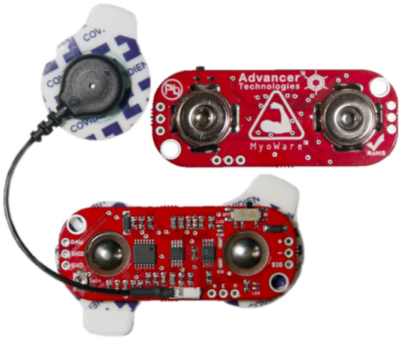


Figure 3.12: *MyoWare*^{TM} electrode module and Covidien gel electrode [61].

Filtering, amplification, rectification, and integration of EMG signals are all provided by *MyoWare*^{TM}. Only the EMG envelope, described as a continuous 0-5 V signal, is included in the output signal. Since the opening/closing commands need two muscle activation areas, two *MyoWare*^{TM} are needed. Every *MyoWare*^{TM} has three electrodes: one for the middle muscle, one for the end muscle, and one for the ground. The end and mid muscle electrode snaps are about 3cm apart, and the reference electrode snap is at the top of a 6cm wire. The setup is built with Covidien gel electrodes.

In order to ensure the interface between the peripheral devices and the computer, an *Arduino Uno* is used. 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 [62].

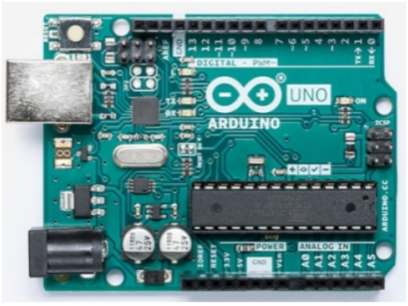


Figure 3.13: *Arduino Uno* micro-controller [62].

Virtual equipment

When a subject is immersed in a virtual environment, a localization of their person, their gesture as well as a realistic visual feedback is necessary. This is possible thanks to the different virtual equipment (**Figure 3.14**) as well 4 base stations placed at the 4 ends of the room. These base stations are fixed and allow, thanks to the infrared emission, to localize all the virtual equipment.

- **HTC Vive HMD:** this virtual reality headset, placed on the head of the subject and connected by a wire to the computer, allows mainly the localisation of the head and the movements, and ensures a visual and auditory feedback.
- **Vive Controller:** this controller allows the localization of the healthy and passive left hand (**Figure 3.15 (1)**). The main role of this hand will be to interact with the prosthesis in order to change the grip pattern (for *Bebionic* and *i-Limb*) or to rotate the wrist of the prothesis (for *Greifer*).
- **Vive Tracker:** this device allows to transpose any object of the real in the virtual world. It is aimed at an armband placed around the subject's right forearm (corresponding to the end of the stump) and thus allows the localisation of the prosthesis (**Figure 3.15 (2)**).

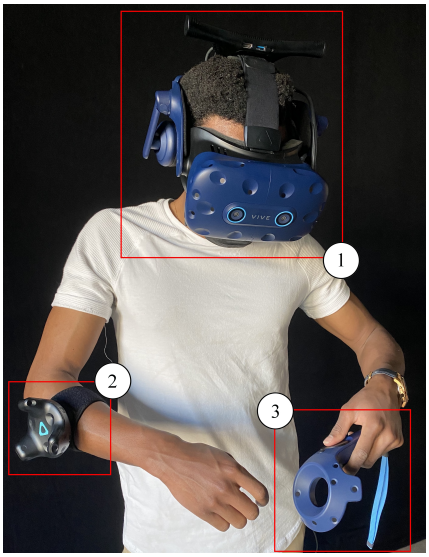


Figure 3.14: Virtual equipment : (1) HTC Vive HMD, (2) Vive Tracker and (3) Vive Controller.

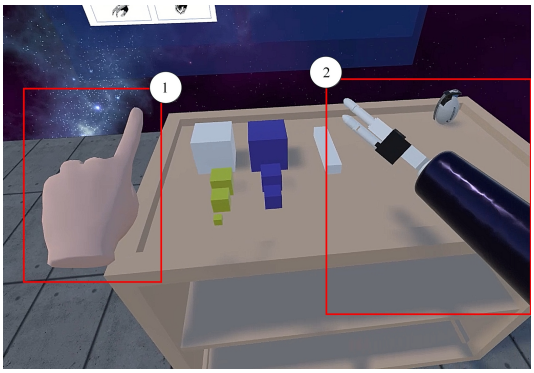


Figure 3.15: Unity Environement : (1) Left hand modeled in VR, (2) Bebionic prosthesis modeled in VR.

Unity Game Engine

The design of a video game can be quite long and complex due to the need to acquire several skills in programming, design, etc. That's why softwares like *Unity, SuperPowers, CryEngine,etc.* have been created in order to facilitate their creation thanks to the use of intuitive commands and assets [4] already prefabricated.

Unity is one of the most widely used free video game platform engines in the world. Developed by *Unity Technologies*, it can be used for the creation of 2D and 3D games. We find for example lots of popular games: *PokemonGO, Hearthstone: Heroes of Warcraft, Cuphead* and *Super Mario Run.*

In the game world, it is possible to create elements, called **Game Objects** (GO), which are an integral part of the scene. Their creation can be done through assets (or be created by the constructor oneself). GOs acts as a container for functional components (considered as its characteristics) that determines the appearance of the GameObject, and what the GameObject does. In addition, there can also be a parental hierarchy between GOs: a GO can be a "parent" or "child" of another GO (e.g the fingers of prostheses are considered to be the children of the hand). This means that the transformation changes of a GO-child will no longer be made in relation to the game world but in relation to its parent.

SteamVR allows the transition from 3D to virtual reality by interacting with different virtual equipment via the computer screen and by making a 360 degree 3D VR game player.

[4] An asset corresponds to a folder containing digital files, free or paid, created by other external people and possible to reuse via "assets store". (e.g. characters, stage sets, objects of all kinds, etc.)

3.4.3 Virtual environment

Once the subject is immersed in the VR environment, they navigates through several scenes. An operator is needed. His role is to assist the subject by interacting with the computer screen, i.e to select the scenes, scroll through the slides, start the activities, adjust the threshold, etc. The structure of the scenes, shown in **Figure 3.16**, is a corridor leading to 4 rooms.

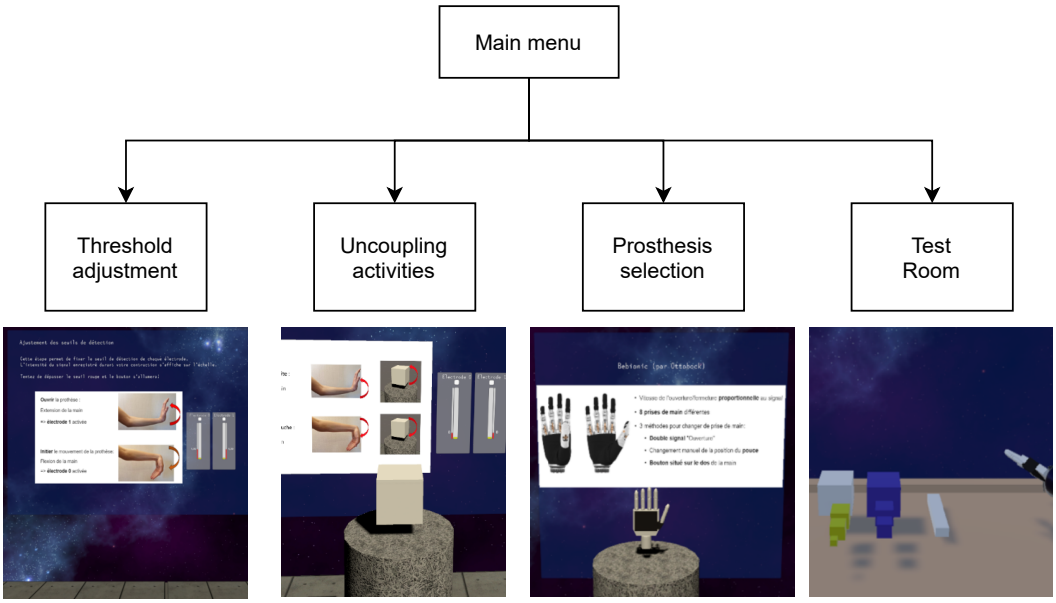


Figure 3.16: The structure is composed of 5 scenes. It is a common corridor, i.e the main menu, leading to 4 rooms, namely the threshold adjustment, the uncoupling activities, the prosthesis selection and the test room. Details related to each room are in the text.

Main menu scene

The *Main menu* is the launching screen of the serious game. It is a common corridor leading to 4 other rooms. For the subjects, this scene is seen as a waiting room, they are immersed in a simple platform surrounded by a spacial view. A visual feedback from the HTC Vive Headset is already available. Hence, the subject can already get familiar with the virtual view.

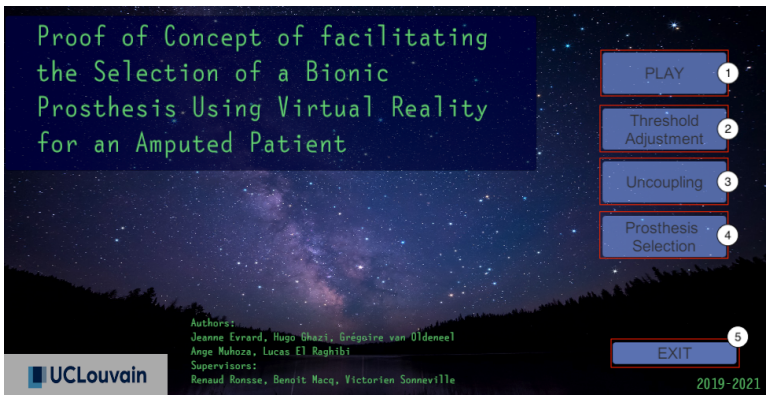


Figure 3.17: Main menu. Interacting buttons leading to: (1) Test Room, (2) Threshold adjustment Room, (3) Uncoupling Room, (4) Prosthesis selection Room, (5) Exit the application.

For the operator, the scene can give access to different buttons, allowing to launch the

different child-scenes (**Figure 3.17**). Game objects and variables are independent in each scene. Although, common parameters can be saved by the operator in order to be kept between several scenes.

Threshold adjustment scene

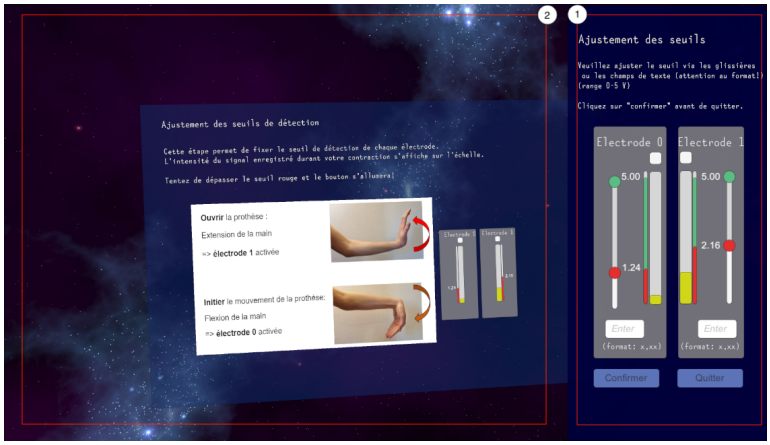


Figure 3.18: Threshold adjustment Room from operator point of view. (1) Operator canvas, (2) Subject point of view.

Firstly, the operator should navigate to the *Threshold adjustment* room, shown in **Figure 3.18**. In this scene, the intensity of the signals collected by the 2 EMG electrodes is displayed in real time on the yellow scale going from 0 to 5 Volts. It allows the operator to set the minimal threshold (red handle) adapted to the subject manually.

It is also possible to modify the maximal emitted signal intensity (green handle) if the subject is not able to reach the value set by default. This will focus the scale around the reachable value, it allows to adapt the game to the range of signals that can be emitted by the subject. Any signal between the threshold and the maximal reachable value produces a visual feedback from the animation controller during the activities of the other rooms, e.g the opening/closing of the prosthesis. The operator has to save the threshold data before going to the next scene.

Uncoupling activities scene

The *Uncoupling activities* room (**Figure 3.19**) aims to fully isolate the learnability of the interface. In this scene, the subject undergoes 3 mini-games allowing to get more familiar with the interface and EMG signals. These mini-games are very simple tasks. They require to use EMG signals to move basic objects.

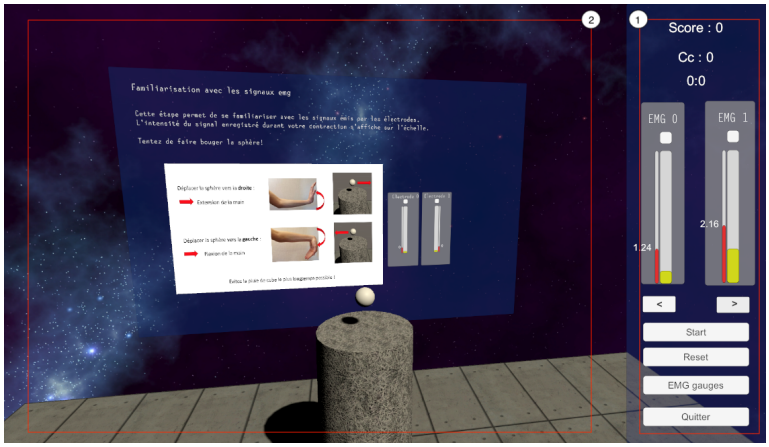


Figure 3.19: Uncoupling activities room from operator point of view. (1) Operator canvas, (2) Subject point of view.

Firstly, the subject has to perform the mini-games with visible EMG gauges, allowing

to observe the current state of the signals emitted. Then, they has to perform it again without visible EMG gauges in order to be in similar conditions as the testing of the prosthesis. The operator has to scroll through the different mini-games and to start them. He also ensures the on/off switch of the visible gauges.

The gauges always stay visible for the operator to check that the electrodes remain in place and that the thresholds are adapted. The recorded data, i.e time on mini-games and number of co-contraction emitted, also appears on the operator canvas.

Prosthesis selection scene

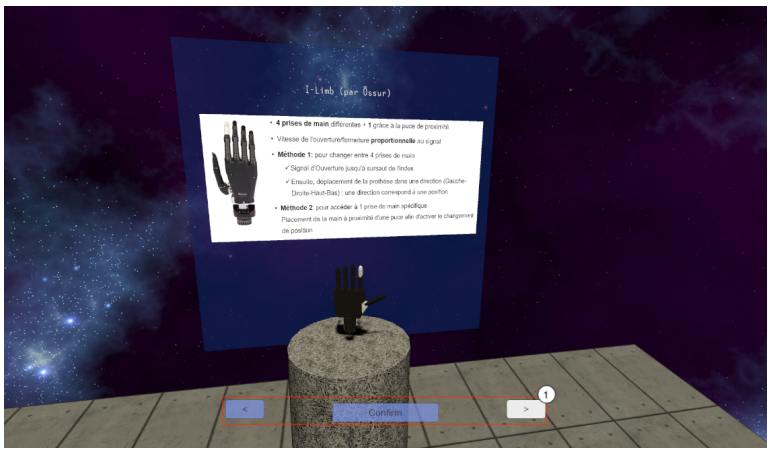


Figure 3.20: Prosthesis selection room from operator point of view. (1) Operator canvas.

The next scene is the *Prosthesis selection* room, shown in **Figure 3.20**. It aims to select the prosthesis and to provide the subject with a quick review of its main features, i.e number of grip pattern implemented, control system of opening and closing, grip pattern changing system.

Each prosthesis disposes of a explanation slide and a preview of itself on a display in the middle of the VR environment. The operator can switch the prosthesis preview and saves the selected prosthesis.

Test Room scene

The *Test Room* (**Figure 3.21**) offers the possibility to test virtually the previously selected prosthesis by performing various tasks. This scene displays a table with cubes of different sizes on top of it. The subject can interact with these objects through the virtual prosthesis to accomplish the tasks. A support slide also appears in the back (not visible in the figure)

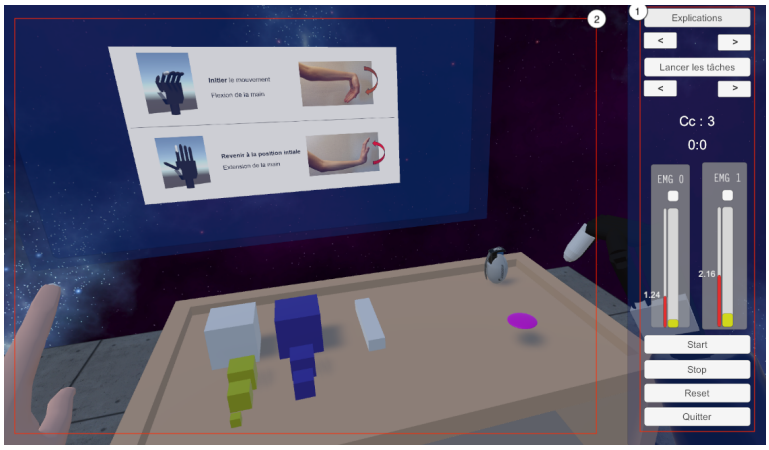


Figure 3.21: Test room from operator point of view. (1) Operator canvas, (2) Subject point of view.

It presents the explanation of the prosthesis and shows the tasks needed to be performed during the session. The operator manages the scrolling between the explanation and

task slides. Similarly as in *Uncoupling activities* room, the operator constantly sees the EMG gauges, to keep an eye on the subject's electrode signals, and the tasks data.

3.4.4 Interface learnability implementation

The will to implement the learnability of the interface started from a simple question: does the device developed in this work have its place in the toolbox of a prosthesis? For this to be the case, the device must be able to measure the usability/learnability of the prosthesis itself. That is to say that the learning of the interface and the prosthesis must be **decoupled**.

The learning of the interface is mainly based on the familiarization with the EMG signals. To facilitate this familiarization, a first step was to find a more **didactic** way to visualize the signals emitted by the subject and the moment from which these signals, by exceeding the threshold, will generate an animation. From this idea was born a series of tasks, i.e **mini-games** (similarly to **Section 2.3.1**), as simple as possible to understand the use of EMG signals. This idea seems to make sense since the learning of myoelectric prostheses by ULA patients also involves the use of mini-games. Moreover, since the prosthesis works all in **speed control**, the same operation has been applied in the mini-games.

The first mini-game (**Figure 3.22**) is the *rotation of a cube* on itself. The speed of rotation depends on the intensity of the signal emitted by the subject and the direction of rotation depends on whether the signal is emitted by the extensor or flexor muscles. This mini-game allows the direct visualization of the impact of a signal exceeding the threshold.

As learning is stimulated by the didactic aspect, the second mini-game (**Figure 3.23**) is more challenging. In this one, it is the *translation of a sphere* which is controlled in speed by the subject. Once the participant is ready, a rain of cubes will start to appear and the participant will have to try to collide with a maximum of falling cubes. Each cube earns 1 point and the activity lasts one minute.

The last mini-game (**Figure 3.24**) seeks to make the translation towards the world of the prosthesis. The goal is to make the participant understand the opening and closing of the prosthesis with a simplified task. The participant controls the *opening and closing of a clamp* in speed. When the participant is ready, a rain of black and white cubes will start above the clamp. The black cubes are to be avoided and the white cubes are to be touched.

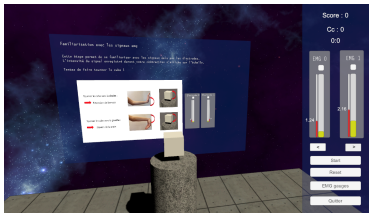


Figure 3.22: Mini-game 1: Cube rotation.

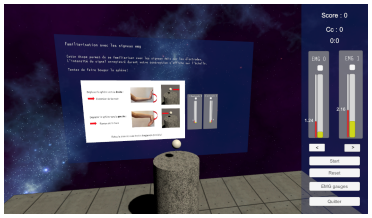


Figure 3.23: Mini-game 2: Sphere translation.

Figure 3.24: Mini-game 3: Clamp opening and closing.

Finally, it was noticed that participants often had difficulty switching from the decoupling activities in the *Uncoupling* scene to the activities with the prostheses in the *Test Room*, because the EMG gauges were no longer displayed. A functionality was therefore added in the *Uncoupling* room to allow to play the different mini-games with or without displaying the EMG gauges for the subjects.

3.4.5 Virtual prosthesis implementation

When modeling a prosthesis, certain **assumptions** about the geometry or command must be made. Indeed, patents cover the design of real prostheses, making most information unavailable. This research focuses on a few methods that were chosen based on the differences between prostheses and what could be accomplished with the tools available. **Table 3.3** overviews the implemented *Greifer*, *i-Limb*, and *Bebionic* prostheses in virtual reality during last year's thesis.

Since this project is in the prototype stage, the current system requires that the virtual prosthesis be located on the participant's right arm. The left hand is therefore modeled by a healthy hand in the virtual environment.

	Greifer (Ottobock)	Bebionic (Ottobock)	i-Limb (Ottobock)
Real prosthesis and virtual model (FreeCAD)			
Opening/Closing	2 electrodes		
Number of grip patterns	1	8	5
Pattern changing	-	Electrode,button,thumb	Electrode,gesture/grip chip
Wrist rotation	Manual	-	-

Table 3.3: Overview of the implemented prostheses (*Greifer* [22], *Bebionic* [23], *i-Limb* [24]).

Greifer

The virtual model of *Greifer* consists of 3 main parts. The first two are mobile parts constituting the clamp and the last one is a static part which is connected to the forearm of the prosthesis. In the Unity environment, 3 GOs compose *Greifer* of which the 2 mobile parts are considered as the children of the static part.

The opening and closing of the clamp are controlled by 2 electrodes (emg0 to close, emg1 to open) whose signal intensity is proportional to the opening and closing speed. This function is totally symmetrical, implying a similar angle of rotation for the two moving parts. In addition, the ULA patient can activate the rotation of *Greifer* wrist manually by a simple touch with his left passive hand.

Bebionic

The virtual model of *Bebionic* is closer to the representation of a real hand. Like *Greifer*, the opening and closing function are controlled by the same 2 electrodes. However, as seen in **Section 1.2.2**, *Bebionic* presents a larger number of grip patterns: among the 14 available, 8 of them have been implemented and divided into 4 groups (**Figure 3.1**).

The change of grip pattern can be done in 3 different ways (namely the electrodes, the thumb position or the button on the back of the hand) and requires a complete opening of the prosthesis before each change. A double opening signal generated via the emg1 electrode allows to switch from one grip pattern to another within the same group.

The thumb has two positions: the lateral one (corresponding to groups 1 and 2) and the opposite one (corresponding to groups 3 and 4). In reality, the transition from one position to another is done manually by the patient and it is implemented virtually by a touch of the healthy hand at the base of the thumb. As for the button located on the back of the hand, it allows the passage between group 1 and 2 and the passage between group 3 and 4 when the latter is pushed by the left hand.

i-Limb

The virtual 3D model of *i-Limb* corresponds exactly to the same model as *Bebionic*, only the color and the change of grip pattern are different. Like the two other prostheses, the opening and closing function are controlled by the same 2 electrodes. There are 5 grasping modes that have been implemented and that are divided into 2 methods as shown in **Figure 3.1**: the gestural control, allowing to obtain 4 grasping modes and the proximity control, allowing to obtain the 5th.

The principle of gestural control lies in the triggering of an index finger jump (obtained by maintaining a long opening signal, emg1) followed by a movement of the prosthesis in one of the 4 directions of space, i.e up, down, left, right, for which a different grip pattern is assigned to each direction.

The principle of the proximity control resides in the passage of the prosthesis close to a proximity chip in order to access a new grip pattern. In this work, the "mouse grip" has been assigned, i.e a position allowing to grasp a computer mouse. As for *Bebionic*, a complete opening of the prosthesis is necessary before each change of grip pattern.

Chapter 4

Results

This chapter presents the results collected during the experimental campaign. First, a summary of the participants' personal information is shown. Then, the results are presented in two parts: the results of the tasks and those of the surveys. Eventually, an analysis of the results is shown.

4.1 Participant demographics

The experimental campaign has been conducted on **13 participants**, i.e 12 able-bodied and 1 ULA participant. Their profiles are resumed in **Table 4.1**.

Subjects	Gender	Age	Profession	Handedness
S01	M	24	Student	R
S02	F	23	Student	R
S03	F	25	Student	R
S04	M	21	Student	R
S05	F	23	Student	R
S06	F	23	Student	R
S07	M	22	Student	R
S08	M	22	Student	R
S09	F	24	Student	R
S10	M	26	Student	R
S11	F	24	Student	R
S12	F	24	Student	L
S13	M	27	Frontlane	L

Table 4.1: Participant demographics.

As announced in **Section 3.2**, the able-bodied group of participants is composed solely of students from *Université Catholique de Louvain*. Concerning the ULA participant, he is a male birth amputee who has been using myoelectric prostheses since the age of 6. Therefore this subject has a lot of experience with EMG signals compared to the able-bodied ones.

Indeed, the ULA participant currently uses *Michelangelo* prosthesis, which is not implemented in the actual state of the prototype. However, the first myoelectric prosthesis he had was *Greifer* and he should switch in the next few months to *Bebionic*. He has always chosen his prostheses based on theoretical descriptions. Because of his upcoming prosthesis change, he has resumed weekly physical therapy sessions in order to re-exercise and prepare himself for his new prosthesis. He is comfortable with the use of his residual limb. In addition, he does not suffer from phantom pain.

4.2 Task results

In this section, we will focus on the results obtained during the realization of the different tasks. As a small reminder, **Table 4.2** briefly reviews the description of the several tasks.

Task	Description
Task 1	In the first task, the subject is asked to reproduce the different grip patterns of the prostheses, one after the other. *Note : This task only concerns Bebionic and i-Limb prostheses.*
Task 2a	The second task consists in the construction of a castle composed of 6 blocks, i.e 5 cubes of different sizes, and 1 rectangular bar.
Task 2b	Once the castle is built, the participant is asked to drop the smallest cube located on top of the castle. *Note: For Bebionic and i-Limb, it was requested that the subject changes his grip pattern in order to be in the "index pointing" position before performing this task.*

Table 4.2: Reminder of the different tasks (**Figures 3.1 and 3.2**).

The participants had to do **3 sessions** of VR spread over 2 weeks. The testing order of the different prostheses was randomized at each session. During each task, the **time** needed to complete it and the number of **co-contractions** emitted were collected.

4.2.1 Typical trial

In order to control the opening/closing of the prosthesis and the change of grip pattern, the participants had to emit particular EMG signals. The EMG signals collected by electrode 0, placed on the flexor muscles, activated the closing of the virtual prosthesis. While electrode 1, placed on the extensor muscles, collected the signals allowing the opening of the virtual prosthesis. An exemple of the signal acquired by the $MyoWare^{TM}$ electrodes is shown in **Figure 4.1**. The resulting analogue signal is in the range of the supply voltage (namely 5V).

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 sent by the *Arduino* controller to the LED 0 (resp. LED 1) for a first visual feedback. LED lighting ensures that the electrodes remain well connected.

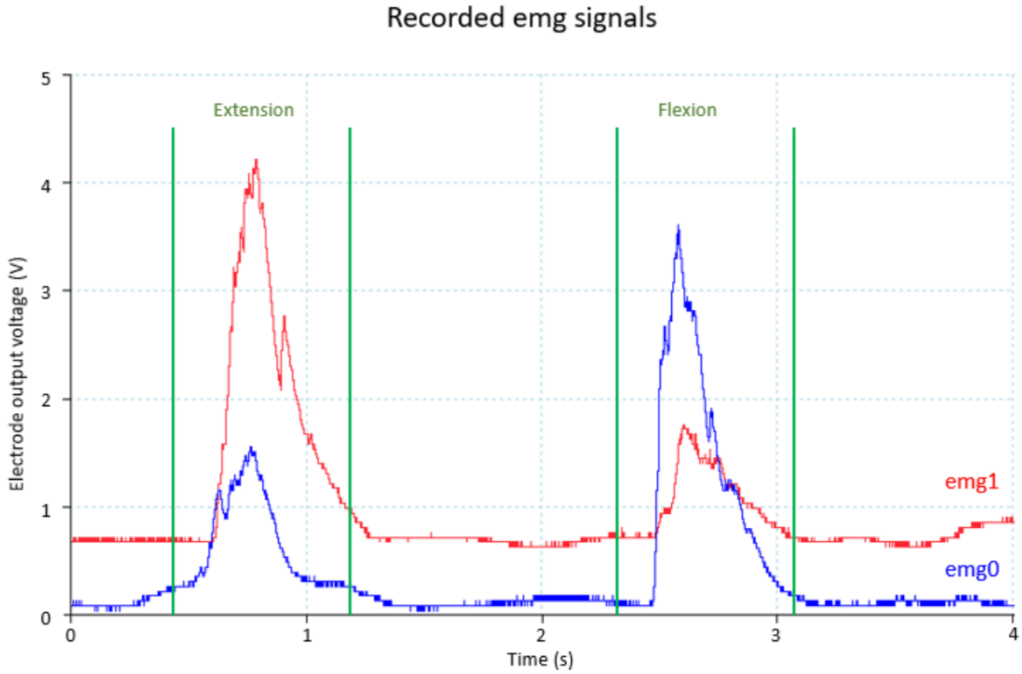


Figure 4.1: Example of signals acquired by the *MyoWare*^{TM} electrodes. Blue: Electrode 0 output signal, Red: Electrode 1 output signal. This graph was recorded by using an external measure device connected to the output electrode wire [42].

The signals emitted by electrode 0 or 1, transmitted to *Unity* by the *Arduino* controller, generate an animation of the prosthesis in the virtual environment when it exceeds a threshold value adapted to each participant. If both signals exceed their respective thresholds at the same time, a co-contraction is generated. Since the prosthesis receives two antagonistic instructions, i.e. simultaneous opening and closing, it will not move. For some myoelectric prosthesis, the co-contraction allows to change the grip pattern or to switch to the wrist control but these functionalities have not been implemented in the current prototype.

In the context of this prototype, we only measured the occurrence of co-contractions and not the time lasted in co-contraction. This choice is based on 2 main reasons: the co-contractions generated by the participants usually last less than a second and we did not manage to implement a system measuring time with a sufficient accuracy in *Unity*.

4.2.2 Task 1

The time needed to perform the first task and the measured co-contraction's occurrence are respectively shown in **Figures 4.2 and 4.3**. The rationale behind the methodology used to present the results is the following: the data from the able-bodied group of participants is used to make a statistical study and a comparison is made with the ULA participant's data.

On the graphs, a boxplot containing the data of the able-bodied group for each session and each prosthesis is shown and in addition to each boxplot, there is a cross

corresponding to the results of the ULA participant. In order to examine the influence of session and prostheses on either time and/or co-contraction's occurrence, a multifactorial ANOVA analysis is done. The hypotheses are defined in **Table 3.2** and the details of the calculations are explained in the **Section 3.3.4**. Two levels of statistically significant difference are defined: *, $p < 0.05$ and ***, $p < 0.001$ allowing to refute the null hypothesis.

Time for task 1

The summary of the time needed across the sessions and the prostheses for the able-bodied group is shown in **Figure 4.2**. During the sessions, the subjects reproduced the different grip patterns using the developed VR system. A decreasing trend is expected between the different sessions. The difference in time across sessions (*, $p < 0.001$) and prosthesis (***, $p < 0.05$) was statically significant. At the end of the last session, the median number of time needed to perform task decreased around a minute compared to the first session for both prostheses. The limb deficient subject (cross) demonstrated a smaller decrease in time between sessions for both prostheses.

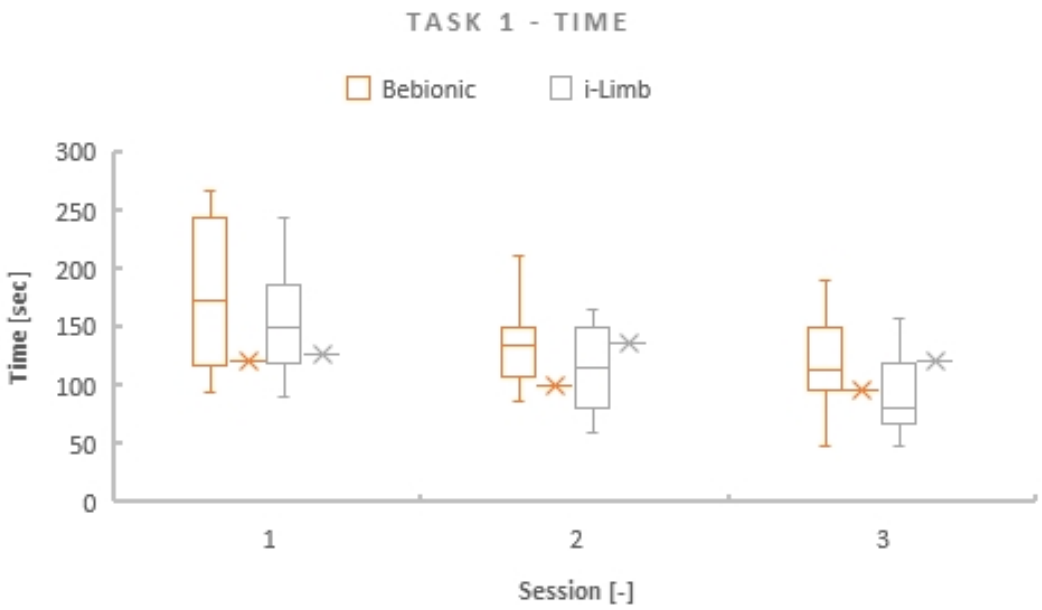


Figure 4.2: The time on task 1 across sessions and prostheses for the subjects in the able-bodied group (boxplots) and the ULA participant (cross). The boxplots depict median (horizontal line), interquartile range (box), and min and max values (whiskers). Note that the time needed consistently decreased across the sessions for both prostheses.

The multifactorial ANOVA, i.e depending on the session and the prosthesis, for the time in seconds needed by the subjects to perform task 1 in the able-bodied group is displayed in **Table 4.3**.

	Significance
Session	< 0.001
Prosthesis	0.016
Session*Prosthesis	0.950

Table 4.3: Time multifactorial ANOVA for task 1. Note that the difference in time is statistically significant for both session (*, $p < 0.001$) and prosthesis (***, $p < 0.05$).

Co-contraction's occurrence for task 1

The summary of the co-contractions's occurrence across the sessions and the prostheses for the able-bodied group is shown in **Figure 4.3**. A decreasing trend is expected between the different sessions. The difference in co-contraction's occurrence across sessions and prosthesis was not statically significant. At the end of the last session, the median co-contraction's occurrence decreased around 5 to 6 co-contractions compared to the first session for both prostheses. The limb deficient subject (cross) demonstrated a higher decrease between sessions for *i-Limb*.

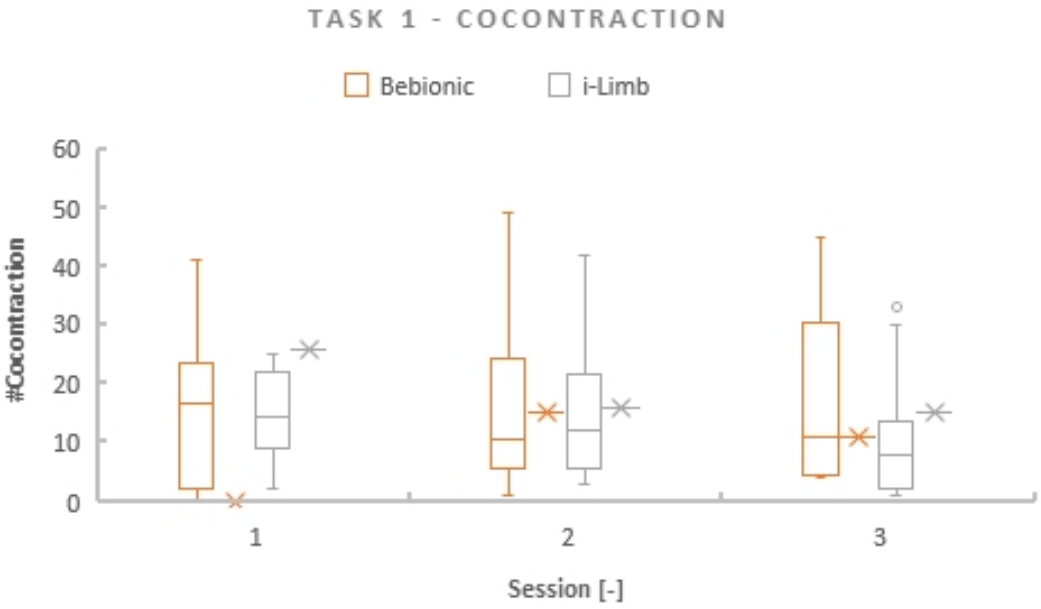


Figure 4.3: The co-contraction's occurrence on task 1 across sessions and prostheses for the subjects in the able-bodied group (boxplots) and the ULA participant (cross). The boxplots depict median (horizontal line), interquartile range (box), min and max values (whiskers), and outliers (round). Note that the co-contraction's occurrence consistently decreased across the sessions for both prostheses.

The multifactorial ANOVA, i.e depending on the session and the prosthesis, for the co-contraction's occurrence emitted by the subjects during task 1 in the able-bodied group is displayed in **Table 4.4**.

	Significance
Session	0.883
Prosthesis	0.408
Session*Prosthesis	0.684

Table 4.4: Co-contraction's occurrence multifactorial ANOVA for task 1. Note that the difference in co-contractions is not statistically significant for any of the factors.

4.2.3 Task 2

The time needed to perform the task 2a and the measured co-contraction's occurrence are respectively shown in **Figures 4.4 and 4.5**. The rationale behind the methodology used to present the results is the same as in task 1.

Time for task 2a

The summary of the time needed across the sessions and the prostheses for the able-bodied group is shown in **Figure 4.4**. During the sessions, the subjects built a block castle using the developed VR system. A decreasing trend is expected between the different sessions. The difference in time across sessions (*, $p < 0.001$) and prosthesis (***, $p < 0.05$) was statically significant. At the end of the last session, the median number of time needed to perform task decreased around a minute compared to the first session for all prostheses. The limb deficient subject (cross) also demonstrated a decrease in time between sessions for each prosthesis.

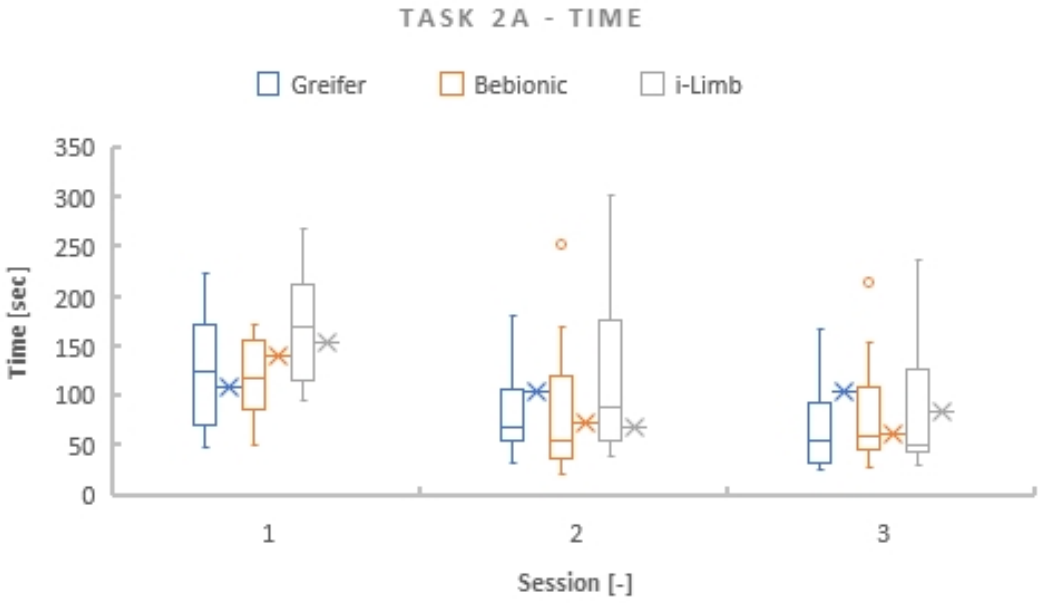


Figure 4.4: The time on task 2a across sessions and prostheses for the subjects in the able-bodied group (boxplots) and the ULA participant (cross). The boxplots depict median (horizontal line), interquartile range (box), min and max values (whiskers), and outliers (round). Note that the time needed consistently decreased across the sessions for each prosthesis.

The multifactorial ANOVA, i.e depending on the session and the prosthesis, for the

time in seconds needed by the subjects to perform task 2a in the able-bodied group is displayed in **Table 4.5**.

	Significance
Session	< 0.001
Prosthesis	0.028
Session*Prosthesis	0.646

Table 4.5: Time multifactorial ANOVA for task 2a. Note that the difference in time is statistically significant for both session (*, $p < 0.001$) and prosthesis (***, $p < 0.05$).

Co-contraction's occurrence for task 2a

The summary of the co-contractions's occurrence across the sessions and the prostheses for the able-bodied group is shown in **Figure 4.5**. A decreasing trend is expected between the different sessions. The difference in co-contraction's occurrence across sessions and prosthesis was not statically significant. At the end of the last session, the median co-contraction's occurrence decreased around 3 to 4 co-contractions compared to the first session for both prostheses. The limb deficient subject (cross) demonstrated a decrease between sessions for each prosthesis.

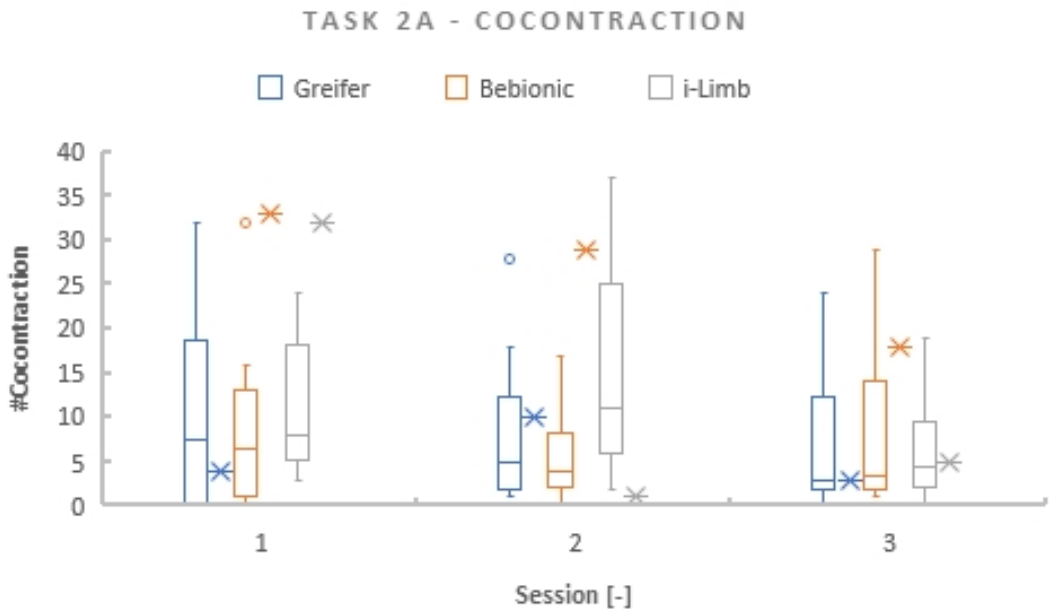


Figure 4.5: The co-contraction's occurrence on task 2a across sessions and prostheses for the subjects in the able-bodied group (boxplots) and the ULA participant (cross). The boxplots depict median (horizontal line), interquartile range (box), min and max values (whiskers), and outliers (round). Note that the co-contraction's occurrence consistently decreased across the sessions for both prostheses.

The multifactorial ANOVA, i.e depending on the session and the prosthesis, for the co-contraction's occurrence emitted by the subjects during task 2a in the able-bodied group is displayed in **Table 4.6**.

	Significance
Session	0.420
Prosthesis	0.277
Session*Prosthesis	0.263

Table 4.6: Co-contraction's occurrence multifactorial ANOVA for task 2. Note that the difference in co-contractions is not statistically significant for any of the factors.

Task 2b

The summary of the results from Task 2b (time and co-contraction's occurrence) across the sessions and the prostheses for the able-bodied group is shown in **Table 4.7**. During the sessions, the subjects drop the smallest block located on the top of the castle. A decreasing trend is expected between the different sessions.

	Sessions	Time	#Co-contraction
Greifer	1 (N=9)	11,00 +/- 28,00	0,11 +/- 0,11
	2 (N=11)	9,72 +/- 14,22	0,27 +/- 0,82
	3 (N=10)	5,50 +/- 7,39	0,00 +/- 0,00
Bebionic	1 (N=11)	26,45 +/- 189,67	2,82 +/- 11,36
	2 (N=11)	11,27 +/- 29,42	1,09 +/- 1,09
	3 (N=9)	7,56 +/- 18,78	0,44 +/- 0,53
i-Limb	1 (N=10)	19,00 +/- 52,89	2,10 +/- 8,54
	2 (N=11)	13,82 +/- 70,36	2,09 +/- 6,49
	3 (N=11)	9,00 +/- 11,60	0,55 +/- 0,67

Table 4.7: Overview of the results obtained for each sessions and prosthesis during task 2b. Notice not all the means and variances (mean +/- variance) are computed on the same sample size (N) due to unavailable results.

4.3 Survey results

The different surveys submitted to the participants can be found in the **Appendix E**. The first type of questionnaire is SUS survey and the second is a before/after VR session survey.

4.3.1 System Usability Scale

The subjects were asked to fill a SUS survey, described in **Section 3.3**, for each prosthesis. The SUS score is computed as explained in that section. The SUS survey's results are presented in the same way as the task results, i.e a boxplot for the able-bodied group's data and a cross for the ULA participant's data.

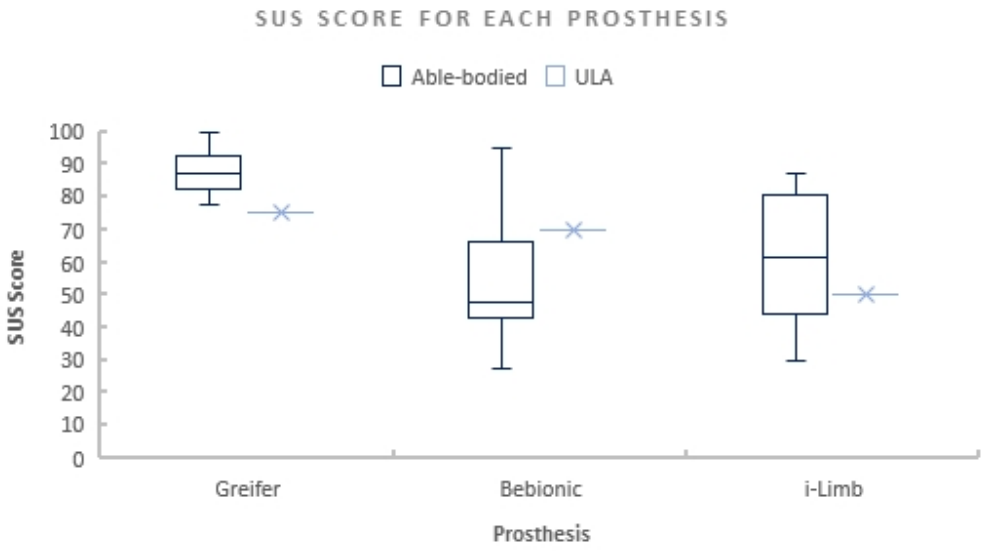


Figure 4.6: The score of the SUS survey across the prostheses for the subjects in the able-bodied group (boxplots) and the ULA participant (cross). The boxplots depict median (horizontal line), interquartile range (box), min and max values (whiskers).

4.3.2 Before/After VR testing

In this questionnaire, the terms "before" and "after" correspond to the moment when the participant completed it, i.e. before or after the VR sessions.

General criteria (from Q3 to Q14)

Based on certain criteria, the subject was asked to rank the prostheses in order of preference. A summary of the results from the able-bodied group and ULA participant is shown in **Table 4.8**.

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

Table 4.8: Results of the survey (from Q3 to Q14) before and after that the subjects have done the VR sessions. The sign "+" indicates the prosthesis the most voted for the first position, and the sign "-", the prosthesis the most voted for the last position.

Daily activities (from Q15 to Q17)

On the basis of 8 activities proposed to the participants, namely eating, dressing, using phone, shopping, cooking, cleaning and maintaining the house, doing laundry, travelling (by car, bicycle, ...), they were asked to tick the activities they would feel comfortable doing with the prosthesis provided.

Table 4.9 compares the results obtained before and after the VR sessions for each prosthesis. The percentages represent the proportion of participants who feel comfortable doing the given activity with the given prosthesis.

	Greifer		Bebionic		i-Limb	
Activity	Before	After	Before	After	Before	After
Eat	46.1%	46.1%	100%	100%	100%	100%
Dress	46.1%	38.5%	100%	100%	92.3%	100%
Use phone	23.1%	15.4%	84.6%	69.2%	100%	76.9%
Shopping	84.6%	69.2%	100%	100%	100%	100%
Cooking	23.1%	30.8%	100%	84.6%	92.3%	100%
Clean and maintain house	38.5%	38.5%	92.3%	92.3%	92.3%	100%
Laundry	61.5%	30.8%	100%	100%	100%	100%
Travel (car, bike, ...)	38.5%	23.1%	69.2%	84.6%	92.3%	92.3%
Average	45.2%	36.5%	93.3%	91.3%	96.1%	96.1%

Table 4.9: For each prosthesis, percentage of the subjects that would be comfortable to do a given activity with this prosthesis (from Q15 to Q17).

Figure 4.7 summarizes the average scores, all activities combined, of each prosthesis before and after the VR sessions.

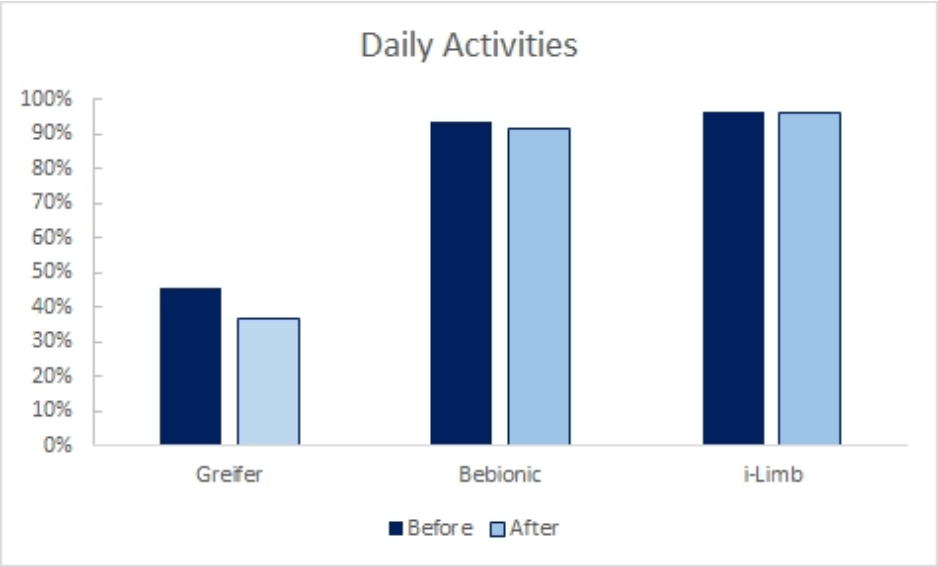


Figure 4.7: Average score of each prosthesis before and after having tested the VR (from Q15 to Q17).

Final choice (Q18 and Q19)

Eventually, the participants had to choose the prosthesis they preferred (Q18). The graphs in **Figure 4.8** show the distribution of the prosthesis choices before and after the VR session.

Figure 4.8: Total percentages of the subjects having chosen the prosthesis, before (left) and after (right) having testing in VR (Q18).

In addition, **Figure 4.9** shows the proportion of participants who changed their mind about which prosthesis they thought was the most suitable for them after testing in VR compared to the proportion of participants who consolidated their choice of prosthesis.

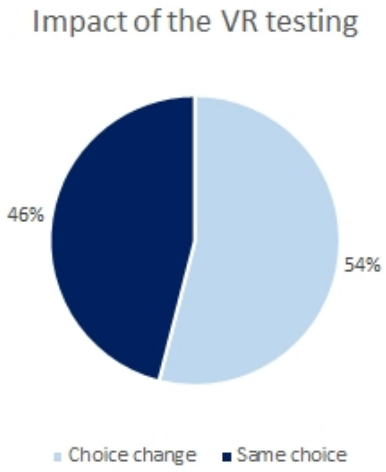


Figure 4.9: Percentages of the subjects having changed or kept their choice of prosthesis after having tested the VR (Q18).

The final question of the second survey (Q19) was to point out the utility of the immersion in VR(**Table 4.10**).

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

Table 4.10: Utility of the VR testing (Q19).

4.4 Results analysis

4.4.1 Task results analysis

Task 1

Number of sessions will impact, with a risk less than 0.1%, the time needed to perform task 1.

Task 1 consisted of reproducing the different grip patterns. As the sessions progressed, the participants began to become accustomed to the different methods of changing grip modes and consequently went faster in each session, as we can observe in **Figure 4.2**. The progression observed between the different sessions corresponds essentially to the learnability of each prosthesis since the mini-games have allowed most of the integration of the learning of the interface and the EMG signals beforehand.
We notice the same tendency in the ULA subject but only for *Bebionic*. Indeed, we can observe that the scores for *i-Limb* remain quite constant. Regarding the timing, the scores of the ULA participant are relatively low compared to the able-bodied group: this can be justified by the fact that he has already been used to EMG signals and to the use of prosthesis for a number of years. This habit also helps to understand why we notice a less clear progression with the ULA participant compared to the able-bodied group.

Selected prosthesis will impact, with a risk less than 5%, the time needed to perform task 1.

Concerning the choice of prosthesis, we can notice in **Figure 4.2**, for each session, that the participants take more time to perform the task with *Bebionic* compared to *i-Limb*. Firstly, it must be underlined that *Bebionic* presents more grip patterns, i.e 8 grip patterns, to be reproduced than the *i-Limb*, i.e 5 grip patterns. Then, the grip pattern changing modes are different between the prostheses, some participants might struggle more with one system than the other. Moreover, *Bebionic* presents 3 "options" to change grips pattern, namely thumb movement, activation button on the back of the prosthesis, double opening signal, compared to *i-Limb* which presents only 2, namely index finger jump for gesture control and proximity chip for proximity control.
Consequently, we notice a better trend with *i-Limb*. This tendency was unfortunately not confirmed with the ULA participant. This non-confirmation could be justified because the ULA subject encountered a difficulty to correctly control EMG signals when his stump was in particular position (left, right, up and down) as *i-Limb* grip pattern changing method required.

Interaction between the number of session and the selected prosthesis will not impact the time needed to perform task 1.

Focusing now on the interaction between the number of sessions and the choice of prosthesis, we notice in **Figure 4.2**, that the steepness of *Bebionic*'s learning curve is higher than *i-Limb* one. However, between session 2 and 3, the learnability of *Bebionic* shows a tendancy to meet an ultimate plateau and not really decrease anymore.
Comparing with the ULA participant's data, a slight improvement can be notice over the sessions for *Bebionic*, but not for *i-Limb*. The ULA participant highlighted that he had much more to learn with the use of *Bebionic* compared to the use of *i-Limb*.

Neither the session, nor the prosthesis, nor their interaction will impact statistically significantly the co-contraction's occurrence emitted in task 1.

Co-contraction's occurrence is a data being more prone to bias than time. Indeed, different reasons could justify it; in particular the readjustment of the participant's thresholds between sessions if needed, or the quality of the participant skin's surface, as well as the good placement of the electrodes which will have an influence on the quality of the EMG signal's transmission.
Based on **Figure 4.3**, we can notice a decrease in the co-contraction's occurrence over the sessions, mainly with *i-Limb*, for the able-bodies group for both prostheses and we also notice that this trend is confirmed for the ULA participant and shows a descending learnability curve as expected. Furthermore, we also observe that the variance in the results with *i-Limb* is lower than with *Bebionic*. It could be explained by the grip pattern changing system which is essentially using long opening signals for *i-Limb* instead of double opening signals that might generate more co-contractions.

Task 2

Number of sessions will impact, with a risk less than 0.1%, the time needed to perform task 2a.

Similarly to Task 1, we notice in **Figure 4.4** an improvement of the time needed to perform Task 2a as the sessions progress. From session to session, participants refined their strategy for creating the castle by either reducing the number of unnecessary movements or by making better use of the healthy hand. However, we also notice the appearance of outlier (during the second and third sessions for the *Bebionic*) which is linked to the participants making false manipulations or breaking their castle.
As for the progression related to sessions, we notice a lower progression between sessions 2-3 compared to sessions 1-2 which could be interpreted as the appearance of a plateau as the sessions progress.
Compared to the ULA participant, we notice a small improvement in the construction time for *Bebionic* and a fairly constant value for *Greifer* between sessions.

Selected prosthesis will impact, with a risk less than 5%, the time needed to perform task 2a.

Concerning the choice of prosthesis, the construction time need to perform task 2a with *i-Limb* and *Bebionic* were expected to be very similar since it was only required to perform simple opening and closing movements, without changing grip patterns. However, as we can see in **Figure 4.4**, the participants tend to take more time with *i-Limb* than with the other two prostheses.
A justification could be the occurrence of involuntary use of different functionalities due to the undesired activation of the long opening signals or double opening signals mainly. We can make the same observation with the ULA participant.

Interaction between the number of session and the selected prosthesis will not impact the time needed to perform task 2a.

In **Figure 4.4**, the almost constant value for *Greifer* by the ULA participant can

be justified by the fact that he was already very used to the EMG signals. However, we notice for *i-Limb* and *Bebionic* a decrease in the construction times justified by a progression in the understanding of the prosthesis functionalities.
Moreover, we can observe the appearance of a plateau, i.e the scores start to be more and more similar over the sessions, justified by a familiarization of the EMG signal.

Neither the session, nor the prosthesis, nor their interaction will impact statistically significantly the number of co-contractions emitted in task 2a.

In **Figure 4.5**, we notice firstly the appearance of outliers linked to a difficulty of EMG signals emission caused by the imposition of particular positions in order to seize the blocks. Secondly, we can notice a decrease in the cocontraction's occurence over the sessions for *Greifer* and *Bebionic* and also that this trend is only confirmed with *Bebionic* for the ULA participant and thus giving a descending learnability curve as expected. Finally, we also notice a rather low number of co-contractions for *Greifer* justified by the fact that the ULA participant was already used to EMG signals with this prosthesis.

Task 2b shows a tendency to be executed faster with Greifer but also less precisely.

Table 4.7 shows the summary of the results collected for task 2b. The means and variances, for each session and prosthesis, are not calculated with the same sample size because it happened that the participants destroyed the castle while trying to perform the task. The task was stopped in order to avoid tiring the participants by making them rebuild the castle.
Since *Greifer* prosthesis did not require a change in grip pattern, the time required to perform the task tended to be lower. However, because the clamp was less accurate virtually than a pointing index finger (as for *Bebionic* or *i-Limb*), the castle was broken more often with *Greifer*.

General comments

Big impact of each individual result in a small sample of subjects.

The sample used for this experimental campaign is 12 able-bodied participants and 1 ULA participant. It is therefore relatively small, and even if some of the ANOVA results show statistical significance, they should be taken in perspective.
The individual impact of each subject remains high, leading to the appearance of outliers as in Task 2 (**Figure 4.4**) when a participant breaks the castle or feels a lot of difficulties with a particular prosthesis or just feels tired during one of the sessions.

Some subjects had more affinity with controlling EMG signals than others.

None of the able-bodied participants had any experience with EMG signals prior to entering the campaign as this was an exclusion criterion. Even though all participants had the opportunity to get familiar with the interface and this type of signal through the mini-games, mastering such signals is not intuitive for everyone. Some people already felt comfortable after the first session, while others still had difficulties during the last session.

Big influence of the adjustment of the threshold and the placement of the electrode on the data collected.

The thresholds were adjusted in several trials before and during the uncoupling mini-games in order to find the ones that best fit the participants before starting the tasks. However, some subjects still had problems adjusting the thresholds.
If the thresholds were too high, the participant emitted fewer co-contractions but had difficulty controlling the opening/closing of the prosthesis and therefore took longer to perform the tasks. On the contrary, if the thresholds were too low, the number of co-contractions increased drastically, which also prevented a good use of the prosthesis. Moreover, once the thresholds were set, they were kept for the 3 sessions in order to have the most consistent results possible. However, it happened that a participant did not feel comfortable with the thresholds of a previous session, for example due to a different placement of the electrodes, thus obliging to readapt the thresholds.

Test order didn't have a major influence on results.

During the sessions, the order of the prostheses was randomized in order to obtain the most homogeneous results possible. However, for ease of use, the participants all started the first session by trying *Greifer*, which is beforehand simpler and more intuitive (as we can confirm from **Table 4.8**). However, we don't observe a real impact by this choice in **Figure 4.4**.

4.4.2 Survey results analysis

SUS results show that Greifer is the most usable prothesis.

From **Figure 4.6**, we can observe that *Greifer* has a better usability than the two other prostheses. This can be explained by the fact that this prosthesis is easier, more straightforward to understand and use. Moreover, this prosthesis had the possibility to control the rotation of the wrist (manually) contrary to the 2 others. We also see that *Bebionic* and *i-Limb* have similar results with the average score of *i-Limb* being slightly better.
For the ULA participant, we can see that the scores of *Greifer* and *Bebionic* are much tighter than in the able-bodied group. The lower score of *i-Limb* is justified because the participant was not convinced by the grip pattern change features of this prosthesis. He had difficulty in giving the closure signal in the positions required by the prosthesis (up, down, left and right).

After the VR sessions, i-Limb was not considered as the most complex prosthesis but as the most functional one (conversely for Bebionic). Greifer was said to be the most robust device before and after VR sessions.

Based on **Table 4.8**, we can observe that the opinion of the participants remains essentially the same before and after the VR sessions except for certain criteria. Indeed, initially *i-Limb* was considered as the most complex prosthesis while after the sessions *Bebionic* took its place. The opposite took place for the functionality criterion.
Furthermore, although *Greifer* is still ranked as the least aesthetic, functional and innovative prosthesis, it is considered the most robust and intuitive prosthesis which certainly contributes to its higher usability score than other prostheses, as we can see

in **Figure 4.6**.
Regarding the ULA participant, he clearly had a preference for *Bebionic*. Having never heard of *i-Limb* before, he ranked it as the most innovative before testing it. After the sessions, he was not convinced by its functionality and found *Bebionic* to be the most innovative.

Based on the 8 proposed daily activities, subjects are more comfortable to use i-Limb prosthesis.

We observe that *i-Limb* prosthesis is better able to perform the tasks of daily life, as shown in **Table 4.9**. While its average score remains the same, 96 %, the distribution of its scores for certain activities will change. For example, all participants felt able to use their phone with *i-Limb* before the virtual test but only 77 % felt able to do so afterwards. On the contrary, some subjects initially did not feel able to dress, cook, clean with the prosthesis but after the sessions these activities went up to 100 %.
Greifer remains the least popular of the three prostheses in terms of activities both before and after. There are considerable differences with the other two prostheses for activities such as using the phone or cooking. *Bebionic* has a score that decreases very slightly from 93 % to 91 % between before and after.
A relevant point was raised by the ULA participant: according to him, it is mainly the size of the residual limb that will dictate with which activities he will feel comfortable or not. Indeed, the influence of the residual limb on elbow flexion and forearm supination and pronation had been highlighted in **Section 1.1.3**. In his case, he feels able to perform, either before or after the VR sessions, all the daily tasks proposed with *Bebionic* and *i-Limb* but only some, namely shopping and travel, with *Greifer*.

Initially, Bebionic was the most chosen prosthesis but after having the VR sessions, more than 2/3 of the subjects preferred i-Limb as a final choice.

Based on theoretical explanations, the participants' preference for the most suitable prosthesis was balanced between *Bebionic*, 54 % and *i-Limb*, 46 % (**Figure 4.8 - Left**). The slight advantage of *Bebionic* can be explained by the fact that the subjects were more reassured by its features based on manual interactions, i.e buttons and thumb rotation.
After virtual testing, 69 % of the participants said they preferred *i-Limb* (**Figure 4.8 - Right**). We can see that having to use the same system to switch from one grip pattern to another with *i-Limb* would be an advantage. Indeed, for *Bebionic*, it is necessary to always remember the currently activated grip pattern.
The device helped the ULA participant to consolidate his choice, since he preferred *Bebionic* before and after the VR sessions.

More than half of the participants changed their choice of prosthesis after having the VR sessions.

Figure 4.9 highlights the impact that the device developed in this work could have. Thanks to the opportunity that is offered to the participants to fully understand and clarify the mechanism of each prosthesis, they are better able to make the best choice. The VR tasks also emphasize the trade-off between the number of grip patterns and the complexity of the prosthesis. Some subjects realized that having many grip patterns

was not necessarily a priority compared to easier control system. This experience is added to the theoretical explanation they receive about the prosthesis in order to consolidate or modify their initial choice.
In the case of this experiment, 54 % of the participants changed their preferred prosthesis after having had the opportunity to test them virtually.

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

Table 4.10 shows that all participants, including the ULA subject, perceive the usefulness of such a tool. Whether it is by consolidating or changing their choice as explained above (**Figure 4.9**) or simply by allowing a better understanding of the use of EMG signals thanks to the visual feedback offered by VR.
Indeed, the ULA participant emphasized that such a tool would have been very useful to him before having his first prosthesis in order to have a clearer vision and to be able to make better choices from the start.

Chapter 5

Discussion

The discussion is separated in 2 parts. First, an interpretation of the results of the tasks and surveys is made. Then, limitations and improvements are discussed.

5.1 Results interpretation

The objective of this work was to develop a tool to facilitate the selection of myoelectric prostheses for ULA patients using VR. Indeed, these patients currently have to choose the prosthesis which would be the most adapted to them on the basis of theoretical explanations often leading to prosthesis rejections. A system is therefore being developed since last year, to offer ULA patients the opportunity to virtually test prostheses available on the market.

In this work, 2 hypotheses have been defined, i.e. the primary and secondary hypotheses. They concern respectively the selection of the most adapted prosthesis based on their "virtual" usability and learnability and the impact of virtual testing on the choice of the subject.

Therefore, an experimental campaign was set up (**Section 3.1**) allowing to collect data based on tasks to be performed by the participants (**Section 4.2**) and on forms (**Section 4.3**). The surface results were previously analyzed (**Section 4.4**). In this section, the background results will be discussed and interpreted in order to conclude the hypotheses.

5.1.1 Selection of the most adapted prosthesis

Prosthesis comparison

The control mechanisms of the prosthesis are not intuitive. They are arbitrary methods developed by manufacturers such as *Ottobock* or *Ossür*. It is therefore logical that the participants have a **subjective** preference for one or the other system. This is because they feel more comfortable with one EMG signal manipulation or have more difficulty controlling another. For example, we can compare the double opening signal required by *Bebionic* which, according to the feedback from the participants, requires more precision than maintaining a long opening signal, required by *i-Limb*. In addition, it was observed that the auditory feedback present when using these grip pattern

change techniques, mainly for the double opening signal, was crucial to facilitate the user.

A factor that follows from these systems and contributes to the usability of the prosthesis is the **control map**. *i-Limb* control map, which allows access to any desired grip pattern regardless of the current grip pattern, is probably easier to use in real life conditions than *Bebionic* control map, which requires to know the currently activated grip pattern at all times. These different reasons may justify why, after having tested virtually, 2/3 of the participants think *i-Limb* is the most suitable prosthesis.

In order to select the most suitable prosthesis, it is important to mix quantitative and subjective data. Indeed, in this kind of process, the subjective aspect plays a crucial role because the final choice will depend on the **application** of the prosthesis. This is evidenced in the table of daily activities, where we see that the participants adapt their opinion on the activities they would feel comfortable doing with the given prosthesis. We can assume that, since our sample is mainly composed of students, and that they do little, if any, manual work, the results of *Greifer* are lower.

However, *Greifer* has some very clear advantages that were highlighted in the experimental campaign. Namely, a superior robustness and intuitiveness which contributes to a general high usability of the prosthesis based SUS score. We can therefore see in which type of application *Greifer* shows all its usefulness.

Learnability

Concerning the discovery of grip patterns mechanism, we observe that *i-Limb* remains the prosthesis with a better learnability curve compared to *Bebionic*. Moreover, *i-Limb* has better scores throughout the sessions than *Bebionic*. Note that *Greifer* does not have any learnability for the grip pattern since there is only one available.

In the framework of prosthesis, we can consider that the users, i.e ULA patients are **expert** users. Let's recall **Figure 1.21**, where the trade-off between the steepness of the learning curve and the efficiency of the ultimate plateau has been emphasized. Indeed, if the device is focused on expert users, the importance of the learning curve is to obtain the best ultimate plateau possible in the usage proficiency and efficiency even if it requires a slower learning, but a faster learning at the expense of a worse plateau, if the device is focusing on a novice user.

When we come to the construction of the castle, we can notice that since the scores remain very close between the different prostheses, we can't easily conclude which one has a better learnability curve.

Although, either for grip pattern mechanism or castle building, even if we can confirm with a statistical significance that there is learning across the sessions for the time needed to perform the task, we can not confirm statistically that the learnability of a prosthesis is better than another.

ULA patient case

The tool developed showed its usefulness in a more realistic situation with the ULA patient. Indeed, the latter was well informed about *Greifer*, which he has used for many years, and about *Bebionic*, which he will receive in the coming months. However, during the theoretical explanation of the prostheses he was intrigued by *i-Limb* and its features. He initially considered it to be the most innovative prosthesis.

However, virtual testing allowed him to confirm that *Bebionic* was the most suitable prosthesis for him and therefore consolidate his initial choice. As a matter of fact, thanks to the implemented system, he was not convinced by the *i-Limb* mechanism finding it unnecessarily complex. In particular, he had difficulties to use properly the method of changing the grip pattern mode using the long opening signal. In fact, this last one imposes to close the prosthesis while having his residual limb in specific position which was more challenging for him.

5.1.2 Impact of virtual testing

Change of opinion

In addition to facilitating the choice of the most suitable prosthesis, the tool developed brings added value by including VR. Indeed, having the opportunity to virtually test the various functionalities of commercially available prostheses influences the opinion that a subject has on them.

This result is essentially justified by the data collected in the before/after survey. We can observe an evolution in the participants' opinion, whether it be in terms of the general perception they have of each prosthesis the daily activities they would feel comfortable doing or the final choice they would make.

The impact of virtual testing on the final choice is particularly noteworthy, as it shows that **more than half** of the participants changed their mind about their preferred prosthesis after the experiment. All the subjects testified that the VR sessions allowed them to better understand the mechanism and the different challenges of each prosthesis.

This highlights the fact that the VR system provides knowledge to the participants that adds to the theoretical explanations received beforehand in order to allow them to make a more judicious choice. For example, as we can see from general criteria, *Bebionic* had been classified as the prosthesis with the best functionality before the experimental campaign and only afterwards, the *i-Limb* took its place (and vice versa for the complexity criterion). Based on this additional knowledge, subjects will either consolidate their initial choice or change their mind. If participants who changed their mind had not had the opportunity to test virtually, then they might have been more likely to reject the initial prosthesis.

Added value of VR

However, why use virtual reality to develop this system? Since the goal is to design a prosthesis choosing system so that ULA patients can try on different prostheses in

a virtual environment, it was essential to create the most realistic simulation. It is therefore sensible to use an immersive virtual reality environment in order to provide patients with the sensation of feeling physically present in the simulation, namely the "*sense of presence*" (**Section 1.3**).

Therefore, it is understandable why all participants tested in this campaign perceived the usefulness of such a tool for the ULA community. In fact, the ULA participant also provided positive feedback on the value of virtual testing. He even noted that he wished he had had access to such a tool before making his first choice of prosthesis several years ago.

Thanks to these feedbacks, it can be concluded that virtual reality is a **relevant tool** adding value to the selection process of myoelectric prostheses by allowing to test and compare them successfully.

5.2 Limitations and improvements

The experimental campaign carried out during this work has allowed to highlight some limitations and improvement tracks for the prototype which are discussed in this section.

5.2.1 Experimental trials

Evaluation methods

During the protocol, participants were asked to perform different tasks, the last of which, i.e task 2b, consisted in dropping the smallest block after finishing the construction of the castle. This task aimed to combine block manipulation and the grip patterns change. However, this task was not the most successful or could not always be performed by the participants because the castle collapsed before the smallest block could be dropped.

For further development, it would be necessary to implement a new task 2b allowing to keep the same objective and being independent from the other tasks in order to guarantee its realization by the participants.

Study population

One of the limitations of the experimental campaign conducted in this work is the sample quality. The size of the sample studied is close to the initial objective of the power analysis, described in **Section 3.3.3**. Moreover, recent articles linking upper limb amputation and RV are based on samples of a similar size, such as in the papers [58] or [63]. However, sanitary restrictions severely limited the diversity of our sample. Indeed, the able-bodied group being composed of students certainly impacted the final results. This could explain why no one selected *Greifer*, which is more suited to manual labor.

Concerning the ULA participant, his strong familiarity with EMG signals and his experience with prosthesis form a source of bias. An amputee with no experience would probably not be able to use our tool with as much ease without

prior training. It is also possible that an inexperienced ULA subject would tire much faster due to the difficulty of controlling the signals and therefore would not be able to try all the prostheses in 1 session leading to an increase of the total amount of sessions required. This raises the important question of where the developed tool will fit in the rehabilitation pathway of an amputee patient (**Figure 2.1**).

The results obtained during this work are therefore to be taken with hindsight, they show more a tendency than strong conclusions about the quality of the implemented tool.

Data measurement

While performing the different tasks, one of the parameters measured was the co-contraction's occurrence. As noticed in **Section 4.4.1**, this measure is quite difficult to evaluate compared to time and one of the reasons could be the modification of the thresholds over the sessions for the same participant.
Indeed, we have encountered the case where the thresholds set in the previous session were no longer appropriate for the participant and in order to perform the task, new thresholds had to be set. This change of thresholds unfortunately indirectly impacts the co-contraction's occurrence performed by the participant.

A second explanation could be the placement of the electrodes. Depending on the area where the electrodes are placed, the quality of the signal can be different for the control of EMG signals. Although, with the ULA participant, we did not encounter any problems of this type since he was already well experienced with the use of the electrodes and therefore was able to guide us correctly in the placement of the electrodes on his stump. If the amputee is not experienced, a solution could be to possibly call upon a physiotherapist for guiding the placement of the electrodes if needed.

Another aspect to improve would be the statistical study of our experimental campaign. One of the tracks that could allow us to obtain more conclusive results for the ANOVA, for the co-contraction's occurrence performed during the different tasks, would be to measure the distribution of time spent in co-contraction compared to the total time for each task.

5.2.2 System architecture

Muscle computer interface

Concerning the prototype, improvements could be made with regards to the electrodes. Firstly, with our prototype, we currently use "wet" electrodes, whereas in the real prostheses available on the market, "dry" electrodes are used. Therefore, in order to be closer to reality, it would be more judicious to replace all the electrodes of our prototype by "dry" electrodes. Secondly, we also encountered a problem of wear for the electrode patches as the experimental campaign progressed. Indeed, by testing several participants over several sessions, the patches became more and more damaged, which reduced the quality of the EMG signals control over the sessions. Although, a box of electrodes was put at our disposal to change the patches when they were damaged.

Hence, an improvement would be to use more resistant electrodes.

Prosthesis implementation

As this prototype is still under development, it currently models only 3 myoelectric prostheses present on the market and only a part of their functionality. The implementation of the prostheses was done by the pioneer of this work, they had limited the implemented functionalities in order to shorten the duration of the test and to facilitate the understanding of the control methods.
Hence, some simplifications have been made, they are listed in the **Tables 5.1, 5.2 and 5.3**. They mainly concern the control of the wrist or access to extra grip patterns.

This arbitrary choice of simplification will induce a source of bias. For example, a participant who is not comfortable with the double opening signals required by *Bebionic* to change grip pattern will tend to choose *i-Limb*. However, this feature also exists in *i-Limb* to access an additional grip pattern mode but is just not implemented in the current version of the prototype.

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 5.1: Summary of all the actions available with the *Greifer* prosthesis. In red, the actions not implemented in the presented tool [42].

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 5.2: Summary of all the actions available with the *Bebionic* prosthesis. In red, the actions not implemented in the presented tool [42].

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 5.3: Summary of all the actions available with the *i-Limb* prosthesis. In red, the actions not implemented in the presented tool [42].

In the previous version of the prototype, the muscle computer interface was not portable and the cables tended to get disconnected by sudden movements. These problems required a greater concentration of the participant who got tired more quickly, thus requiring a not too long sessions. The current version of the prototype has corrected this problem and justifies the possibility of implementing more functionalities of the prosthesis in VR for the next versions of the software. However, increasing the realism of the implemented prosthesis will require the participants to memorize a larger control method map which is not an easy exercice.

Based on the ULA participant's opinion, the virtual prostheses tended to replicate the real ones well and allowed the levels of complexity of each prosthesis to be highlighted. Although, an important limitation of having a virtual prosthesis model is that the weight and inertia of the prosthesis is not taken into account. These criteria are however part of the key elements in the selection of the most suitable prosthesis for a subject and are part of the main challenges of current prosthesis design.

Further applications

After discussions with the ULA participants, it became clear that the tool developed in this project could be used in different ways. Not only could it be used to facilitate the selection of a myoelectric prosthesis but it could also contribute to the rehabilitation process.

As shown in the **Section 2.2**, there are already systems in place that allow ULA patients to learn to master an EMG-controlled device. In particular, the use of mini-games as implemented in the prototype to facilitate the learning process thanks to the playful aspect. Therefore, even if the tool developed in this work is a pioneer in the concept of virtual replication of commercially available myoelectric prostheses, it should be kept in mind that it could be useful in other applications.

The current system requires the virtual prosthesis to be on the subject's right arm or residual limb. This is due to the prototype state of the project and because

it was essentially focused on proving a concept by testing mainly able-bodied participants and few ULA participants. The ULA subject who participated in the campaign was a right limb amputee, so the improvement of making the game usable for left arm amputee patients has not been made. For future applications of the prototype, this should be one of the first improvements to make it suitable for all patients.

Conclusions

In his journey, the amputees will have to choose the prosthesis that they consider the most suitable for them. This choice is not easy, even though it is decisive for their quality of life. Each prosthesis on the market has a different complexity and it may seem difficult to make a choice based only on their theoretical descriptions. This contributes to the high rates of prosthesis rejection in ULA patients (**Section 1.4**). Therefore, the relevance of the project, initiated last year and continued by us this year, has all its sense.

In order to contribute to a decrease in the rejection rate, this work sought to facilitate the choice of ULA patients. To do this, one idea was to provide the opportunity for these individuals to test the geometry and functionality of different myoelectric prostheses using virtual reality. Although there are already systems linking VR and upper limb prostheses, they focus mainly on the rehabilitation process and not on the selection of myoelectric prostheses (**Section 2.2**). The concept proposed in this work is therefore, as far as we know, pioneering in its field.

Within the framework of this work, the validation of two hypotheses was targeted. The primary and secondary hypotheses concerned respectively the selection of the most adapted myoelectric prosthesis based on "virtual" usability and learnability and the impact of virtual testing on the choice. In order to achieve this objective, a series of experimental trials were set up requiring participants to perform tasks in the virtual environment and to complete surveys (**Section 3.1**). The experimental campaign was conducted on 12 able-bodied participants and 1 ULA. The results of the able-bodied group were analyzed with a bifactorial ANOVA (**Section 3.3.4**). The aim was to demonstrate (or not) the impact of the factors, i.e. the number of sessions and the prosthesis used, and/or their interaction on the measured data, i.e the time needed to perform the task and the co-contraction's occcurence during it. In order to allow this experiment, a tool implemented last year and improved during this work, based on the geometry and functionalities of 3 commercialized prostheses, i.e. *Greifer*, *Bebionic* and *i-Limb* has been developed (**Section 3.4**). For the muscle prosthesis interface, 2 electrodes and an *Arduino* are used. As for the virtual environment to perform the tasks, it was developed with *Unity*.

Based on the results obtained, a comparison of the implemented prostheses was made in order to highlight their strong and weak points concerning their functionality, usability and learnability (**Section 5.1.1**). Moreover, the participation of the ULA subject allowed to build confidence at the level of the realism and the relevance of the developed device. Regarding the impact of virtual testing (**Section 5.1.2**), all subjects certified that the experience allowed them to better understand the mechanisms and

challenges of each prosthesis. They were therefore able to build a relevant opinion in order to make a more appropriate choice for their own needs by either consolidating their choice or changing their mind. Indeed, more than half of the participants changed their minds about their choice of prosthesis after the experiment. This impact is amplified by the added value of VR, namely the "*sense of presence*" that allows participants to feel physically testing the prostheses. Thanks to these feedbacks, it can be concluded that virtual reality is a successful tool to test and compare prostheses.

To sum up, by testing prostheses virtually, the complexity and non-intuitiveness of their controls can be better understood. The developed tool duly contributes well to its initial purpose by facilitating the choice of myoelectric prosthesis. Moreover, the developed tool has room for many possible improvements both in the quantity of prostheses and functionalities implemented and has shown its usefulness in other applications such as the rehabilitation process. Therefore, it was decided to make it open-source in order to contribute to the ULA community.

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Appendix A

Grip patterns

Bebionic prothesis offers 14 different grip patterns in which 8 of them are possible with an opposite thumb position and 6 others with the thumb in lateral position. A description of each grip pattern either in opposite or lateral position is given in this appendix.

Thumb in lateral position

Figure A.1: **Column Grip -** "In column grip, the thumb stabilizes the index finger while the remaining fingers close into the palm. This creates a rigid index finger useful for pushing buttons, switches, and levers" [23].

Figure A.2: **Finger Point -** "Intricate tasks like pressing small buttons, typing on a keyboard, or tapping a touchscreen are all possible with finger point. With the thumb in the non-opposed position, the index finger can be isolated while the rest of the fingers close against the palm" [23].

Figure A.3: **Key Grip -** "With the thumb in lateral position, key grip closes it against the side of the index finger. This is ideal for grasping thin, flat objects such as magazines, keys, and credit cards. This position allows users to keep objects in their line of sight" [23].

Figure A.4: **Mouse Grip -** "Whether you are working in the office, browsing the internet, or playing video games, the mouse grip allows you to operate a computer mouse. The thumb and little finger close to hold the side of the mouse, while the middle and ring fingers provide additional stability. The index finger clicks the mouse button using open and close signals" [23].

Figure A.5: **Open Palm Position -** "Open palm fully opens the hand to provide a flat surface when the thumb is in the lateral position. This is effective for carrying plates, bowls, or trays" [23].

Figure A.6: **Relaxed Hand Position -** "When not actively using the hand, the relaxed hand position gives the bebionic a natural and lifelike appearance. The thumb is positioned toward the palm in the lateral position with the remaining fingers slightly flexed" [23].

Thumb in opposition

Figure A.7: **Tripod Grip -** "Tripod grip brings the thumb in contact with the index and middle fingers, allowing the grasp of everyday items like pens, car keys, coins, and other small objects. The ring and little fingers close until they meet resistance or the close signal stops" [23].

Figure A.8: **Pinch Grip -** "With pinch grip, the thumb and index finger are adjusted to make contact. This is useful when picking up a wide range of small objects including coins, car keys, lids, and pens" [23].

Figure A.9: **Power Grip -** "Power grip allows for easy and secure holding of round or cylindrical objects such as bottles, handles, and other household objects" [23].

Figure A.10: **Hook Grip -** "When carrying objects like a shopping bag or briefcase, the hook grip provides the perfect solution. This hand position can be accessed via a partially closed power grip" [23].

Figure A.11: **Active Index Grip -** "In active index grip, the index finger is controlled and positioned independently. This works well for typing or with trigger mechanisms like spray bottles, hairdryers, or light duty power tools" [23].

Figure A.12: **Precision Closed Grip -** "Precision closed grip provides a quick, reliable way of picking up and moving small objects. The index finger contacts the thumb while the rest of the fingers close onto the palm, increasing visual access to objects" [23].

Figure A.13: **Precision Open Grip -** "With precision open grip, small objects can be manipulated with the thumb in opposition. When a close signal is applied, the thumb moves to the midpoint range and pauses. The index finger is then active while the middle, ring, and little fingers remain extended" [23].

Figure A.14: **Finger Adduction -** "Finger adduction brings the fingers together naturally as they close, allowing for grasping of thin objects. This is useful for holding utensils while eating, brushing teeth, picking up papers, and more" [23].

Appendix B

Gantt chart

The following page present the Gantt chart that we followed during this project.

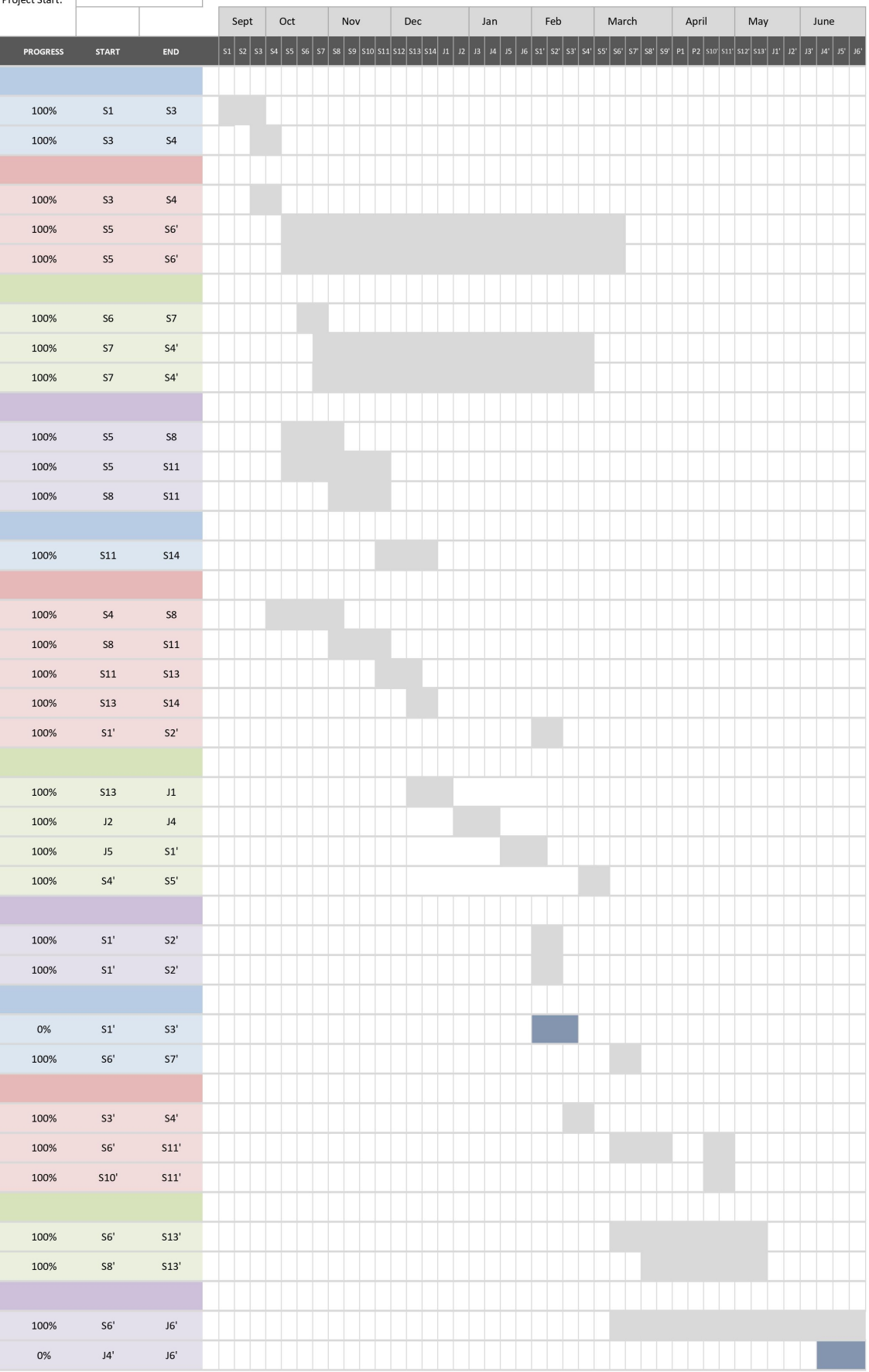
Master thesis plan

UCLouvain
Ange Muhoza

Lucas El Raghibi

Project Start: ma, 9-21-2020

TASK	ASSIGNED TO	PROGRESS	START	END
Familiarization with last year thesis				
Reading of the last thesis		100%	S1	S3
Presentation about our understanding		100%	S3	S4
Revisit state of the art				
Documentation about implemented prosthesis		100%	S3	S4
Research about potential other prosthesis		100%	S5	S6'
General documentation		100%	S5	S6'
Meeting with people from the field				
Meeting with AmptrAide CEO		100%	S6	S7
Research of potential subject		100%	S7	S4'
Meeting with ULA patient		100%	S7	S4'
Discovery of Unity and the code				
Familiarization with Unity		100%	S5	S8
Acquisition of the needed materials		100%	S5	S11
Understanding of the last year prototype		100%	S8	S11
Reproduce some of last year results				
Castle building experimentation		100%	S11	S14
Scope of the contribution				
Familiarization with usability and learnability		100%	S4	S8
Uncoupling between interface and prosthesis		100%	S8	S11
Design of the uncoupling protocol		100%	S11	S13
Assestment of uncoupling prototype		100%	S13	S14
Second round of assestment		100%	S1'	S2'
Design of the protocol				
Define protocol objective		100%	S13	J1
Establish sample and session time		100%	J2	J4
Evaluation and analysis method		100%	J5	S1'
Iteration on the protocol		100%	S4'	S5'
Improvement of the interface				
Prototype board		100%	S1'	S2'
Portable system of the hardware		100%	S1'	S2'
Improvement of the virtual environment				
Adaptation of the game for left hand amputee		0%	S1'	S3'
Adaptation of the evaluation method		100%	S6'	S7'
Experimental study				
Trial of the protocol		100%	S3'	S4'
Healthy subject		100%	S6'	S11'
ULA amputee subject		100%	S10'	S11'
Analysis of results				
Statistical evaluation		100%	S6'	S13'
Discussion of the result		100%	S8'	S13'
Thesis report and final presentation				
Writting of the thesis		100%	S6'	J6'
Preparation of the presentation		0%	J4'	J6'



Appendix C

Informed Consent

An informed consent was designed for this experiment. It covers the following points:

- Objective and description of the experiment.
- Promoter of the experimentation.
- Voluntary participation.
- Benefits and the risks linked to the experimentation.
- Protection of private life.
- People to contact if you have questions about the experiment

The informed consent is shown in the following pages.

[Objet]	Consentement Eclairé Information au participant	UCLouvain École polytechnique de Louvain Date d'application : 17/03/2021

INFORMATION AU *PARTICIPANT*

Faciliter la sélection d'une prothèse myoélectrique du membre supérieur en utilisant la réalité virtuelle

Vous êtes invité(e) à participer de façon volontaire à une expérimentation. Avant d'accepter d'y participer, il est important de lire ce formulaire qui en décrit l'objectif et les modalités pratiques. Vous avez le droit de poser à tout moment des questions en rapport avec cette *expérimentation*.

Objectif et description de l'expérimentation

Il s'agit d'une expérimentation qui devrait inclure environ 10-12 *participants et participantes, tous* en Belgique.

L'objectif de cette expérimentation consiste à faciliter le choix de prothèse myoélectrique en utilisant la réalité virtuelle pour les patients amputés des membres supérieurs.

Si vous acceptez de participer à cette expérimentation, il vous sera demandé devous familiariser avec l'environnement virtuel et les 3 différentes prothèses myoélectriques implémentées dans le jeu sérieux. Le jeu sérieux dont il est question est un jeu vidéo implémenté dans un environnement de réalité virtuelle, et qui permet de mesurer votre capacité à contrôler une prothèse du membre supérieur. Le but recherché est de trouver la prothèse qui vous serait la plus adaptée et voir si l'essais en réalité virtuelle a impacté/influencé votre choix.

Il vous sera demandé de participer à l'expérimentation pendant environ 3 sessions de 1 heure étalées sur 2 semaines.

Promoteur de l'expérimentation

Le promoteur de l'expérimentation est l'Université catholique de Louvain (UCLouvain)

Participation volontaire

Votre participation à cette expérimentation est entièrement volontaire et vous avez le droit de refuser d'y participer. Vous avez également le droit de vous retirer de l'expérimentation à tout moment, sans en préciser la raison, même après avoir signé le formulaire de consentement. Vous n'aurez pas à fournir de raison au retrait de votre consentement à participer ; toutefois, les données collectées jusqu'à l'arrêt de la participation à l'expérimentation font partie intégrante de celle-ci. Votre refus de participer à cette expérimentation n'entraînera pour vous aucune pénalité ni perte d'avantages.

Bénéfices et risques

Nous ne pouvons vous assurer que si vous acceptez de participer à cette *expérimentation,* vous tirerez personnellement un quelconque bénéfice direct de votre participation.

Cependant, les informations obtenues grâce à cette étude peuvent contribuer à une meilleure connaissance du choix de la prothèse myoélectrique la plus adaptée chez un patient amputé du membre supérieur.

Il n'y a aucun risque de participation à cette expérimentation hormis une éventuelle rupture de confidentialité des données.

Protection de la vie privée

Votre identité et votre participation à cette expérimentation demeureront strictement confidentielles. Vous ne serez pas identifié(e) par votre nom ni d'aucune autre manière reconnaissable dans aucun des dossiers, résultats ou publications en rapport avec l'étude. Les gestionnaires des données seront Ange Muhoza et Lucas El Raghibi. Les données collectées dans le cadre de cette étude seront conservées 20 ans après la fin de l'étude, en accord avec les prescriptions du Décret Royal du 18 mai 2006, article 24.

La protection des données personnelles est assurée par la loi du 30 juillet 2018 relative à la protection de la vie privée et par les réglementations européennes (règlementation générale européenne sur la protection des données à caractère personnel [RGPD] du 25 mai 2018) et belges en vigueur. Ces droits sont également garantis par la loi du 22 août 2002 relative aux droits du patient.

Selon le RGPD, vous disposez d'un droit de regard sur le traitement de vos données. Si vous avez des questions à ce sujet, vous pouvez contacter le responsable de la protection des données du centre d'étude à l'adresse suivante : privacy@uclouvain.be

En cas de plainte concernant le mode de traitement de vos données, vous pouvez contacter l'Autorité Belge de Protection des Données : Rue de la Presse 35 - 1000 Bruxelles - Tél. : 02 274 48 00 - e-mail : contact@apd-gba.be

Personnes à contacter si vous avez des questions à propos de l'expérimentation

Si vous estimez avoir subi un dommage lié à l'expérimentation ou si vous avez des questions, voulez donner un avis ou exprimer des craintes à propos de l'expérimentation ou à propos de vos droits en tant que participant à une expérimentation, maintenant, durant ou après votre participation, vous pouvez contacter :

Responsable de l'étude : Ange Muhoza ou Lucas El Raghibi

Téléphone : 0494/53.34.34

FORMULAIRE DE CONSENTEMENT ECLAIRE *AU PARTICIPANT*

1. Je soussigné(e) (NOM, Prénom(s)), ……

déclare avoir lu l'information qui précède et accepter de participer à l'expérimentation "Faciliter la sélection d'une prothèse myoélectrique du membre supérieur en utilisant la réalité virtuelle"

2. On m'a remis une copie de ce formulaire de consentement éclairé signé et daté, ainsi que de la note d'information destinée au participant. J'ai reçu une explication concernant la nature, le but, la durée de *l'*expérimentation et j'ai été informé(e) de ce qu'on attend de ma part. On m'a donné le temps et l'occasion de poser des questions sur l'expérimentation ; toutes mes questions ont reçu une réponse satisfaisante. L'intervention m'a été expliquée en détails, avec les effets secondaires et les risques connus potentiels.
3. Je suis libre de participer ou non, de même que d'arrêter l'expérimentation à tout moment sans qu'il soit nécessaire de justifier ma décision et sans que cela n'entraîne le moindre désavantage.
4. En signant ce document, j'autorise l'utilisation des données me concernant dans le respect de
    - la loi belge du 30 juillet 2018 relative à la protection de la vie privée ;
    - la loi du 22 août 2002 relative aux droits du patient ;
    - la loi du 7 mai 2004 relative à l'expérimentation sur la personne humaine ;
    - les réglementations européennes (règlementation générale européenne sur la protection des données à caractère personnel [RGPD] du 25 mai 2018) et belges en vigueur.
5. Je n'ai subi aucune pression physique ni psychologique indue pour ma participation à l'expérimentation
6. Je consens de mon plein gré à participer à cette expérimentation.

…… ……/……/20……

Nom, prénom et Signature — Date (jour/mois/année)

du (de la) *patient(e)/participant(e)*

Je, soussigné, Mme/Mlle/M. (NOM, Prénoms) …… confirme que j'ai expliqué la nature, le but et la durée de l'enquête au (à la) *patient(e)/participant(e)* mentionné(e) ci-dessus.

…… ……/……/20……

Signature de la personne qui procure l'information — *Date (jour/mois/année)*

Appendix D

Visual Support used during the VR Session

The following slides are written in French current version of the thesis is made in French. Those slides were designed in last year's thesis [42].

GREIFER - Explications

1

Ouvrir la pince (Extension de la main)

Fermer la pince (Flexion de la main)

2

Rotation du poignet:

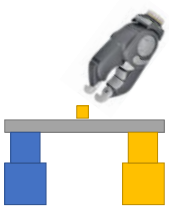
toucher le poignet avec l'autre main.

3

GREIFER – Tâches

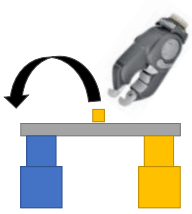
4

Construisez un château de cubes!



5

Une fois le château construit, faîtes tomber le petit cube



6

BEBIONIC - Explications

7

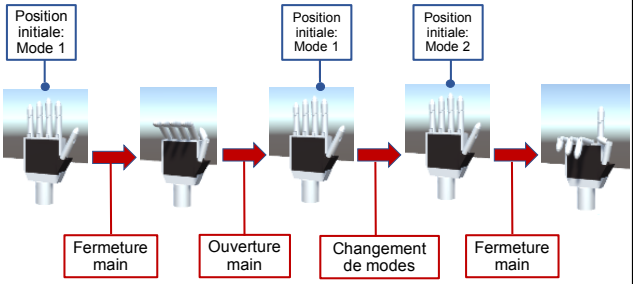
Initier le mouvement

Flexion de la main

Revenir à la position intiale

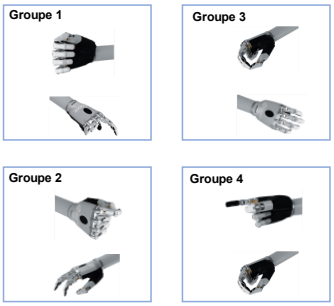
Extension de la main

8



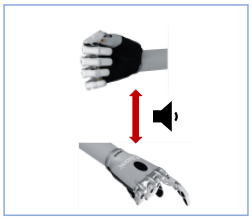
9

Les 8 positions de main sont réparties en 4 groupes



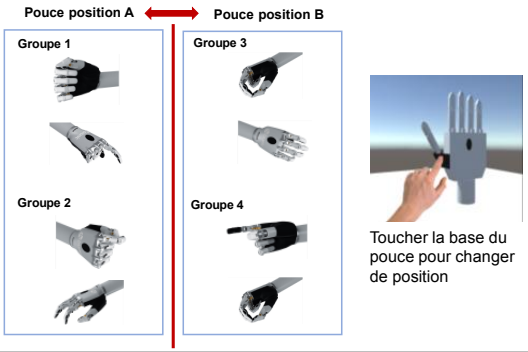
10

Changement au sein d'un même groupe



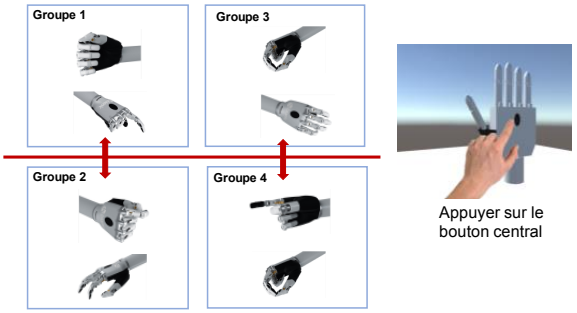
Double signal d'ouverture quand la main est déjà ouverte

11



Toucher la base du pouce pour changer de position

12



Appuyer sur le bouton central

13

BEBIONIC - Tâches

14

Tâche 1:
Reproduire les mouvements suivants

15

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

Prise latérale (Groupe 1)

1/5

16

- ✓ Double signal d'ouverture quand la main est déjà ouverte
- ✓ Initier le mouvement

Index pointé (Groupe 1)

2/5

17

- ✓ Appuyer sur le bouton situé sur le dos de la prothèse
- ✓ Initier le mouvement

Poussoir (Groupe 2)

3/5

18

✓ Appuyer sur la base du pouce pour changer sa position

✓ Initier le mouvement

Pince (Groupe 3)

4/5

19

✓ Appuyer sur le bouton situé sur le dos de la prothèse

✓ Initier le mouvement

Gâchette (Groupe 4)

5/5

20

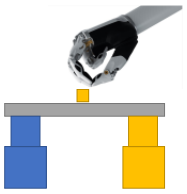
Tâche 2: Manipuler les blocs

21

Construisez un château de cubes!

Pour accéder à la position de pince qui se trouve dans le **groupe 3**

⇨ Venir toucher le bouton sur le dos de la main



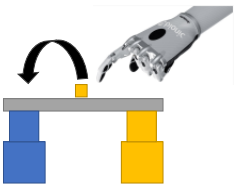
22

Une fois le château construit, faîtes tomber le petit cube avec la prothèse en position doigt pointé

Pour accéder à la position de doigt pointé qui se trouve dans le **groupe 1:**

⇨ Venir toucher la base du pouce

⇨ Double signal d'ouverture

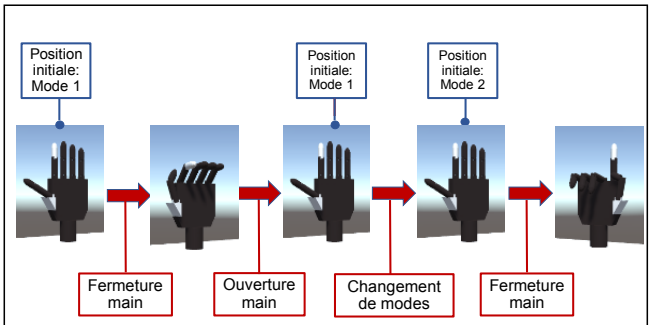


23

ILIMB - Explications

24

25

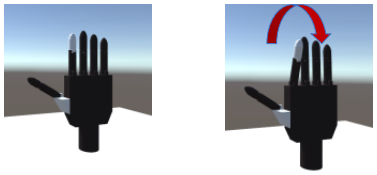


26

Méthode 1
Pour changer le mouvement de main initié

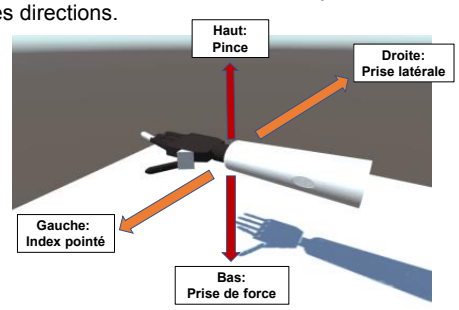
27

Maintenir un long signal d'ouverture, jusqu'à obtenir un sursaut de l'index



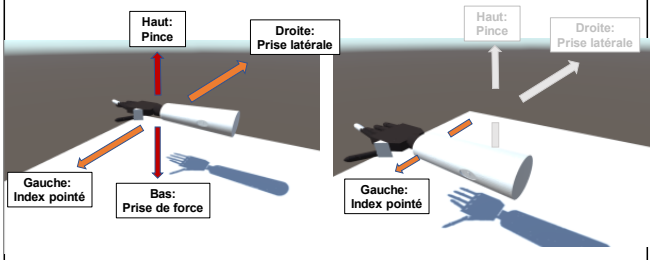
28

Une fois le sursaut de l'index obtenu, déplacer son bras dans une des directions.



29

Bouger dans la direction, puis attendre 1 seconde sans bouger, le nouveau mode est alors activé

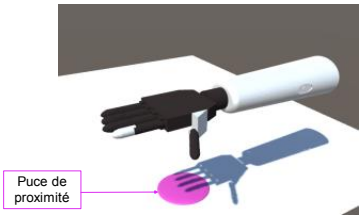


30

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

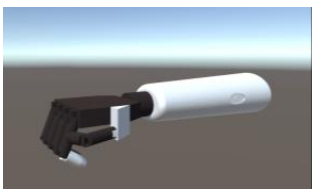
33

Tâche 1:
Reproduire les mouvements suivants

34

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

Prise latérale

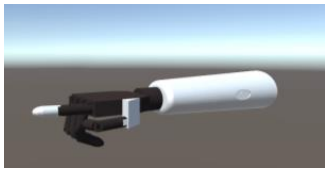


1/5

35

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

Index pointé



2/5

36

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

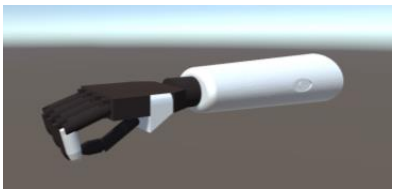
Pince

3/5

37

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

Prise de force

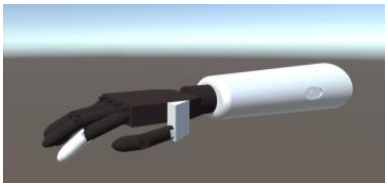


4/5

38

- ✓ Placer la prothèse au-dessus de la **puce de proximité** rose
- ✓ Initier le mouvement

Prise souris



5/5

39

Tâche 2: Manipuler les blocs

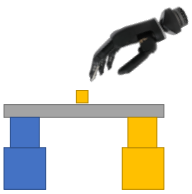
40

Construisez un château de cubes!

Pour accéder à la position de pince:

⇨ Sursaut de l'index en maintenant signal d'ouverture

⇨ Déplacement de la prothèse vers le **haut**



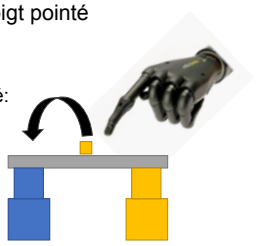
41

Une fois le château construit, faîtes tomber le petit cube avec la prothèse en position doigt pointé

Pour accéder à la position de doigt pointé:

⇨ Sursaut de l'index en maintenant signal d'ouverture

⇨ Déplacement de la prothèse vers la **gauche**



42

Appendix E

Opinion Survey

E.1 SUS survey

A system usability scale survey [59] was used to asses the virtual usability of the 3 prosthesis. It is presented in the following pages and can be accessed at the following link:

Online SUS Survey: usability of the prosthesis

Questionnaire d'opinion - Utilisabilité des prothèses

Ce questionnaire est à remplir après avoir eu l'occasion de tester l'environnement virtuel.

Le but de ce questionnaire est de recueillir votre sentiment personnel concernant chacune des prothèses. Pour chaque questions, vous devez choisir sur l'échelle entre 1 - "Pas du tout d'accord" et 5 - "Tout à fait d'accord", pour chacune des prothèses,. Il n'existe pas de bonne ou de mauvaise réponse.

* Obligatoire

* Ce formulaire enregistrera votre nom, veuillez renseigner votre nom.

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). *

2. Je pense que je pourrais utiliser cette prothèse fréquemment. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

3. Je trouve cette prothèse inutilement complexe. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

4. Je pense que cette prothèse est facile à utiliser. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

5. Je pense que j'aurai besoin de l'aide d'un technicien pour être capable d'utiliser cette prothèse *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

6. J'ai trouvé que les différentes fonctions de cette prothèse ont été bien intégrées. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

7. Je pense qu'il y a trop d'incohérence dans cette prothèse. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

8. J'imagine que la plupart des gens seraient capable d'apprendre à utiliser cette prothèse très rapidement. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

9. J'ai trouvé cette prothèse très lourde à utiliser. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

10. Je me sentais très en confiance en utilisant cette prothèse. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

11. J'ai besoin d'apprendre beaucoup de chose avant de pouvoir utiliser cette prothèse. *

	1	2	3	4	5
Pince Greifer	○	○	○	○	○
Main Bebionic	○	○	○	○	○
Main I-limb	○	○	○	○	○

12. Avez-vous d'autres remarques ?

Ce contenu n'a pas été créé ni n'est approuvé par Microsoft. Les données que vous soumettez sont envoyées au propriétaire du formulaire.

4/18/2021

Microsoft Forms

E.2 Before/After VR session survey

Two before/after VR opinion surveys were designed during last year's thesis [42], 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 described. 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

Appendix F

Data Management Plan

A DMP has been completed along this experiment. It has been done on dmponline.be. It covers several aspects such as:

- Description of the project.
- Data collection.
- Data documentation and metadata.
- Ethical and legal issues.
- Storage and backup.
- Data selection and preservation after research.
- Data sharing.

The final version of the DMP is shown in the next pages.

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

version September 2019

Admin details

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

Principal Investigator / Researcher Ange Muhoza

Description Nowadays, prostheses have a great impact on the daily life of upper limb amputees (ULA) since they allow them to perform a large number of tasks. However, the selection of the most suitable prosthesis is becoming more and more difficult due to the growth of new technologies that increase the quantity of prostheses available on the market. Moreover, this difficulty is accentuated by the fact that patients do not have the opportunity to test them. The aim of this study is to facilitate the choice of prosthesis. For this purpose, a series of experimental trials was conducted using a tool that offers ULA patients the possibility to virtually test prostheses. The study included 12 able-bodied participants and 1 ULA participant. The virtual environment was built with Unity and virtual control of the prostheses is enabled by 2 electrodes placed on the forearm or residual limb. Currently, 3 commercially available myoelectric prostheses are implemented in the prototype. Based on this experience, a comparison of the different implemented prostheses on the basis of their functionality, usability and learnability has been made. Moreover, the impact of virtually testing on the prosthesis chosen by the subject was highlighted.

Institution Université catholique de Louvain

Administrative Data

Date of first version

The first version of the Data Management Plan was made on 16th March 2021

Date of last version

The data management plan was changed on 12th June 2021

Data collection

What is the purpose of the data collection/generation and its relation to the objectives of the project?

The purpose of the data collection is to compare participants' opinions of each myoelectric prosthesis before and after virtually testing it in our VR environment using a questionnaire-based computer. This will ultimately improve the selection of the most suitable prosthesis for the patient.

Moreover, the comparison over several sessions of elements such as the timing to perform certain tasks or the number of co-contractions (corresponding to the sending of signals with contradictory information) allow to certify the ease of use and learning of the prototype.

To whom might the data be useful (‘data utility’)?

Firstly, the aim of this work is a proof of concept 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.

Secondly, the final purpose of this work will be beneficial for upper limb amputees seeking to select the most suitable prosthesis for them. Indeed, by executing some virtual tasks, the patient should be better able to understand the control of the different available prostheses.

Finally, the different data collected will also be useful for research as the protocol developed for prosthesis selection via virtual reality is innovative.

What data will you collect or create?

We have 2 types of data. The first are quantitative data and correspond to the measurement of the time that the patients take to perform our tasks as well as the number of co-contractions (whose origin comes from the simultaneous activation of the 2 EMG signals producing the sending of 2 contradictory information to the prosthesis).The latter tends to represent a feeling of stress or panic from thesubject. The second type of data collected is a quantitative opinion data collected via questionnaires and corresponds to the participants’ opinion of each myoelectric prosthesis before and after testing it virtually in our VR environment. The aim was to evaluate the potential change of vision that the subjects had of the 3 prostheses. Moreover, in order to measure the global usability of the studied system, a SUS questionnaire is used.

How will the data be collected or created?

During each session, the subjects have to perform different tasks with the prostheses and each task is timed and the number of co-contractions is measured, thanks to counters that we have implemented in the virtual environment. These data are called "quantitative data" and their measurements are tabulated in an Excel file (to which only the authors of the experimental campaign have access). While the quantitative data of opinion are collected thanks to opinion questionnaires that the participants (in total 13: 12 valid and 1 ULA) will have to fill in before and after the immersion in the virtual reality. Each questionnaire takes about 5 to 10 minutes to complete and the answers are stored in a Google Form (whose access is also restricted to the authors of the experimental campaign).

Data documentation and metadata

How will you document the data?

This work is done as part of a thesis at Louvain School of Engineering. The data will therefore be documented in a report with their explanation. The different aspects of the prototype (from a hardware and software point of view) will also be explained and therefore the reading of this document will allow the readers to understand how to interpret the data as well as the possibility to understand how to reproduce the experimental campaign as well as the reproduction of the prototype. (Every question and every

possible answer will be documented)

Ethical and legal issues

How will you manage any ethics and confidentiality issues?

During the experimental campaign, personal and confidential data will be collected. Therefore, each participant in the experiment will be asked to sign an informed consent to allow us to collect, use and store and/or share their data. In order to protect the identity of the participants, we proceed by anonymizing them by creating names in the form of code and access to the data is controlled and only the authors of the thesis and their promotors can have access to it.

How will you manage intellectual property rights issues?

No patents will be developed in this thesis since it was decided to make it open-source in order to contribute to the ULA community. Therefore the question of intellectual property does not arise.

Storage and backup

How will you store and backup data during research?

As previously stated, the data collection is primarily stored on Excel and Google Form files. However, in the long run, the data will be stored on a server of UCLouvain in order to be accessible for years to come. As available solutions, the institution recommends using File Service (OASIS), NextCloud or SharePoint, depending on the size of your data so that the data is never deleted as well as to guarantee its security.

The description of the different storage solutions offered by UCLouvain can be found here: https://uclouvain.be/fr/universite-numerique/rdm/store-uclouvain.html

How will you ensure that stored data are secure?

Data security risks are very minimal. We control access to the data by allowing only members of the research team to have access. In addition, data will be anonymized so that participants' identities cannot be traced.

Data selection and preservation after research

Which data should be retained for preservation and/or sharing?

Since this work is being done for a thesis, all data will be kept at the end of the thesis and we have no obligation to destroy the data after the end of the thesis.

What is the long-term preservation plan for the selected datasets?

At this time, no long-term preservation plan for the selected datasets has been thought of as we are in the process of completing a thesis that will end in June 2021.

Latter on, the data will be store on an UCLouvain server in order to be accessible for the next years as mentioned before.

Data sharing

Are any restrictions on data sharing required?

The data collected contains personal data and therefore each participant had to sign an informed consent to give us permission to use their data. No restrictions on this sharing have yet been established.

The article written about this subject will include an access to the data and the materials needed.

How will you share data selected for sharing?

The selected data will be shared in the writing of a scientific article that will be published afterwards as well as in the writing of a thesis report that will be accessible according to the conditions of the UCLouvain

Responsibilities and resources

Who will be responsible for data management?

The responsible for data management will be Ange Muhoza, Lucas El Raghibi, Renaud Ronsse, Benoît Macq, Victorien Sonneville.

Will you need additional resources to implement your DMP?

No additional resources is needed to implement our DMP

Appendix G

Statistical computation

G.1 Power analysis

The summary of all the intermediate results to compute the sample size for a 2-way ANOVA, for both tasks, with power (1- β) = 0.80, are shown in the **Tables G.1 andG.2**.

		Task 1				
Factors	Variable	Partial eta^2	f	df	#groups	Sample size
Sessions	Time	0.556	1.12	2	6	13
	Cc	0.784	1.90	2	6	9
Prosthesis	Time	0.640	1.34	1	6	10
	Cc	0.129	0.38	1	6	56
Interactions	Time	0.009	0.09	2	6	1064
	Cc	0.258	0.59	2	6	32

Table G.1: Intermediate results to the power analysis based on data of Task 1 (see **Figure 3.1**).

		Task 2a				
Factors	Variable	Partial eta^2	f	df	#groups	Sample size
Sessions	Time	0.683	1.47	2	9	13
	Cc	0.752	1.74	2	9	12
Prosthesis	Time	0.009	0.01	2	9	1064
	Cc	0.021	0.14	2	9	453
Interactions	Time	0.097	0.33	4	9	117
	Cc	0.179	0.47	4	9	61

Table G.2: Intermediate results to the power analysis based on data of Task 2 (see **Figure 3.2**).

G.2 ANOVA Calculation

An ANOVA test was performed for the analysis of the data collected during the experimental campaign. In this appendix, we find the details of the calculations of SS, DoF and MS in order to calculate the statistical test.

Test data

- x_{ijk} : ith individual having the modality j of the variable A (i.e first factor) and the modality k of the variable B (i.e second factor), i.e. in the cell (j,k)
- M : overall mean of X on all the observations
- M_{jk} : average of X in the cell (j,k)
- $M_{j.}$ average of X over all the cells having the modality j of the variable A
- $M_{.k}$: average of X over all the cells having the k modality of the variable B
- N : total number of subjects
- n_{jk} : number of subjects in the cell (j,k)
- $n_{j.}$ number of subjects in the set of cells having the modality j of the variable A
- $n_{.k}$: number of subjects in the set of cells having the k modality of the variable B
- J : number of modalities of the variable A
- K : number of modalities of the variable B

Calculation of the Sum of Squares (SS)

If each sample has the same size n, we show that :

$$SS_{total} = SS_A + SS_B + SS_{A*B} + SS_{within}$$

with :

- Sum of the squares of the differences between each observed score and the overall mean = measure of total variability independent of treatments A and B : $SS_{total} = \sum_{i=1}^{N} \sum_{j=1}^{J} \sum_{k=1}^{K} (x_{ijk} - M)^2$
- Sum of the squares of the differences between the mean of each group of variable A and the overall mean = measure of variability due to treatment A : $SS_A = \sum_{j=1}^{J} n_{j.}(M_{j.} - M)^2$
- Sum of the squares of the differences between the mean of each group of variable B and the overall mean = measure of variability due to treatment B : $SS_B = \sum_{k=1}^{K} n_{k.}(M_{.k} - M)^2$
- Sum of the squares of the differences between the mean of each group resulting from the combination of the modalities of variables A and B and 3 means, that of each group of variable A, that of each group of variable B and that of all the observed scores = measure of the variability of the interaction between variables A and B : $SS_{A*B} = \sum_{j=1}^{J} \sum_{k=1}^{K} n_{jk}(M_{jk} - M_{j.} - M_{.k} - M)^2$
- Sum of the squares of the differences between each observed score and its within-group mean resulting from the combination of the terms of variables A and B = measure of the variability within each group resulting from the combination of the terms of variables A and B : $SS_{within} = \sum_{i=1}^{N} \sum_{j=1}^{J} \sum_{k=1}^{K} (x_{ijk} - M_{jk})^2$

Calculation of Degrees of Freedom (DoF)

Table G.3 contains all the degrees of freedom useful to calculate the Mean Squares afterwards.

	Total	Variable A	Variable B	Interaction A*B	Within
DoF	N-1	J-1	K-1	(J-1)(K-1)	N-(JK)

Table G.3: Degree of Freedom

Calculation of the Mean Squares (MS)

The Mean Squares are obtained by dividing the Sum of Squares by the number of Degrees of Freedom (**Table G.4**).

	Total	Variable A	Variable B	Interaction A*B	Within
MS	$\frac{SS_{total}}{DoF_{total}}$	$\frac{SS_A}{DoF_A}$	$\frac{SS_B}{DoF_B}$	$\frac{SS_{A*B}}{DoF_{A*B}}$	$\frac{SS_{within}}{DoF_{within}}$

Table G.4: Mean Squares

Remark : Even if $SS_{total} = SS_A + SS_B + SS_{A*B} + SS_{within}$, the same is not true for the variance ($MS_{total} \neq MS_A + MS_B + MS_{A*B} + MS_{within}$)

Appendix H

System architecture: Additional Information

H.1 Experimental setup

The setup used during the experiment described in **Figure 3.11** with the improvements made this year is shown in **Figure H.1**.

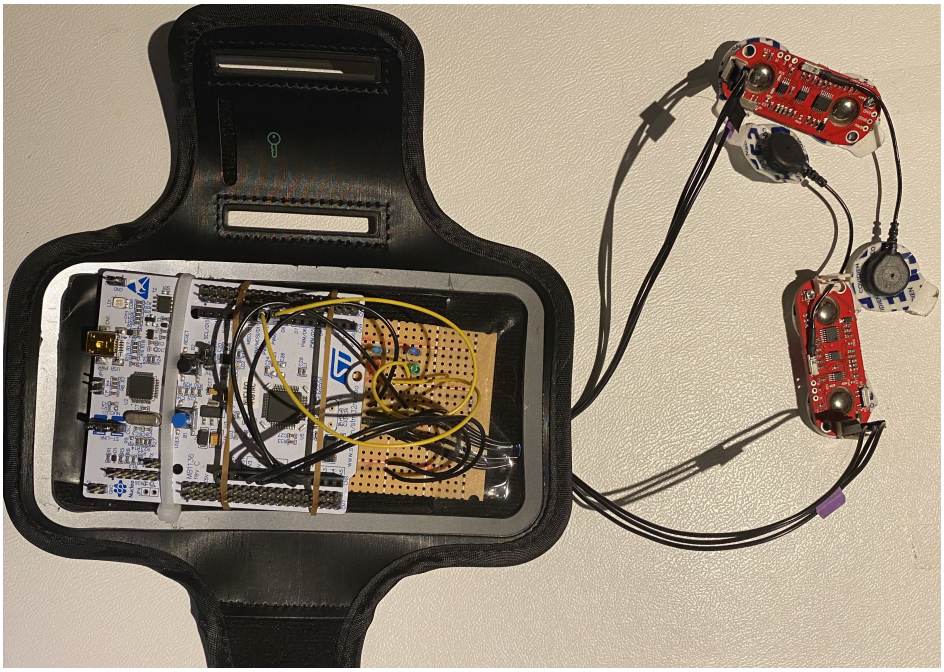


Figure H.1: Picture of the setup used during the experiment.

H.2 Additional files

A description of the algorithm used for each prosthesis is detailed in **Figures H.2, H.3 and H.4**. Those algorithm has been designed during last year's thesis.

Greifer (Ottobock)

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();
```

Figure H.2: Greifer script algorithm [42].

Bebionic (Ottobock)

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);
```

Figure H.3: Bebionic script algorithm [42].

i-Limb Quantum (Össur, Touch Bionic)

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);
```

Figure H.4: i-Limb script algorithm [42].

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