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MASTER'S THESIS

A virtual reality environment for experiments in assistive robotics and neural interfaces

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I, Samuel BUSTAMANTE-GÓMEZ, declare that this thesis titled, "A virtual reality environment for experiments in assistive robotics and neural interfaces" and the work presented in it are my own. I confirm that:

- I have written the dissertation myself and have not used any sources and aids other than those indicated.
- I have not included data generated in my laboratory rotation nor my essay rotation and already presented in the respective laboratory and essay reports.

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EBERHARD-KARLS-UNIVERSITÄT TÜBINGEN

Abstract

Graduate School of Neural Information Processing

Master of Science

A virtual reality environment for experiments in assistive robotics and neural interfaces

by Samuel BUSTAMANTE-GÓMEZ

I present ArmSym, a simulated robotic arm in a virtual reality (VR) environment. The system originated on the need of a testbed in which we could run research on human interaction with upper limb prostheses and wheelchair-mounted robotic arms. In my thesis, I write the motivations of the system, describe the methods for its development, and present a pilot scientific experiment that contextualized ArmSym in the domain of robotic prosthesis for shoulder disarticulation amputees. We intended to test psychological metrics that evaluate the interaction of the user with the robot. Recruiting healthy subjects, we found evidence of a self-reported perception of embodiment of a prosthesis in absence of realistic cutaneous touch, supporting previous studies in the topic. We also found out that the degree of control influences factors that contribute on device acceptance according to a technology acceptance model, most interestingly computer anxiety. We believe that the system and this pilot experiment points us towards interesting research directions in human-robot interaction for assistive robotics and neural interfaces.

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This work would not have been possible without the great input from several people in many different contexts. First, I would like to thank my supervisor, Prof. Dr-Ing. Moritz Grosse-Wentrup. From our first discussion in Spring 2017, he always encouraged me to pursue my ideas on assistive robotics, and his vision from his expertise in BCI is plasmed on this work. I am very grateful for his constant supervision and his encouragement to approach my thesis in a scientific way. I would also like to thank Dr. (c) Vinay Jayaram, who very closely accompanied my work, and always encouraged me to approach my scientific curiosity. I have no doubts that Vinay is going to become a great supervisor.

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Lastly, I would like to thank my family and friends for the incredible support during the thesis and my master's degree. The histogram of *'git commit'* times of ArmSym clearly displays a peak around 7 pm. Therefore, it would not have been possible to develop the system without borrowing time from them. Special thanks to those who were always there, specially Marili Korympidou, Sarah Strauss, Khaled Nasr, my sister Paula Bustamante, and my parents Gloria & Javier. My highest appreciation goes also to all the students of my cohort at the Graduate School for Neural Information Processing, who have made these two years not only endurable but also tremendously fun.

Contents

List of Figures

List of Tables

List of Abbreviations

IK	**I**nverse **K**inematics control
PM	**P**rosthesis **M**imicking control
BCI	**B**rain **C**omputer **I**nterface
BMI	**B**rain **M**achine **I**nterface
EEG	**E**lectro**e**ncephalo**g**raphy
sEMG	**S**urface **E**lectro**m**yo**g**raphy
ARM	**A**ssistive **R**obotic **M**anipulator
NI	**N**eural **I**nterface
BW	**B**arrett **W**am robotic arm
DoF	**D**egree **o**f **F**reedom
TMR	**T**argetted **M**uscle **R**einnervation
SSVEP	**S**teady **S**tate **V**isually **E**voked **P**otentials
PA	**P**ositive **A**ffect
NA	**N**egative **A**ffect

A note on the terminology: Often, the terms "brain-machine interface", "brain-computer interface", and "neural interface" are used interchangeably in the literature. I use BCI for systems that use computers as end-effectors, *e.g.*, that control a computer cursor by means of brain signals, and BMI for the control of any kind of machine, specially a robot. However, in the context of signal processing algorithms, both terms are indeed interchangeable. A NI, on the other hand, is understood here as a system that serves as a pathway between the central nervous system and an external device. NIs is therefore a more general term which contains not only BCIs and BMIs, but also systems that record signals from the muscles and the nerves.

Dedicated to my mother

Graduation day from the engineering school. Medellín, Colombia, April 2016.

"Liebes kleines Mütterlein, nun darf ich endlich bei Dir Sein. Die Sehnsucht und die Einsamkeit erlösen sich in Seligkeit".

"Dear little mother, finally I can be with you. The longing and the sollitude fade away in happiness".

"Querida pequeña madre, finalmente puedo estar contigo. El anhelo y la soledad se pierden en felicidad".
Nico – Mütterlein (Desertshore, 1970)

Chapter 1

Gentle introduction

Science fiction has always given us an ambitious look into robotic assistive devices. In one of the most recent seasons of the British long-running Sci-Fi drama Doctor Who, we are introduced to a character named Nardole, played by Matt Lucas. A constant companion to the series main character, The Doctor, Nardole survives beheading by being attached to a huge dexterous robotic body. He receives in later episodes a more anthropomorphic chassis, but viewers experience some of his struggles: unresponsive limbs, noisy joints due to friction, and screws that fall from the robot all the time. He executes however incredible control over the robotic limbs. This leads the viewer to hypothesize about the benefits and perquisites of a robotic body, either as a replacement or as an enhancing tool. Could we use robots to help humans with motor impairments, for example people with amputations? Could we use anthropomorphic robots in our daily lives as assistants or even in augmented ways of experiencing reality?

Although this idea of using robots as enhancement devices has been present in popular culture for a long time, assistive robots are still far away from the vision portrayed in science fiction. Only few technologies have been exploited commercially, mainly in the domain of prostheses. One of the most impressive examples is the BeBionic hands, which are dexterous anthropomorphic robots with multiple life-like grip patterns. Others technologies are still in iterative processes in academia, specially those in the field of brain-robot interfaces. To my knowledge, the most advanced development in this area is the work of the group of Wodlinger & colleagues: a tetraplegic patient achieved 10-dimensional control of a robotic arm, showing the potential of future technologies using an invasive Brain-Machine Interface (BMI) (Wodlinger et al., 2015).

There are many different groups of patients who could benefit from assistive robots, mainly in two clusters: amputees and paralyzed patients. From the latter, maybe the most known type is traumatic spinal cord injury. Other user groups that may benefit from assistive robots include patients with muscular dystrophy, amyotrophic lateral sclerosis and spinal muscular atrophy; stroke survivors, and people with tremors or spasticity (Blom and Stuyt, 2017).

Our virtual reality (VR) system, nicknamed ArmSym, comes in this context as a tool for testing and developing new methods. Using a fully-immersive head-mounted display, we can run experiments not only in patients but also in healthy participants, which is is usually difficult. The purpose and idea of ArmSym can be understood in the light of our previous work, which I introduce in the next section.

1.1 Previous work and motivation

The present Master's Thesis was preceded by a 10-week internship project in accordance with the guidelines of the Graduate School. My work was focused on conveying control to a robotic arm using a Brain-Machine Interface. The manipulator[1] autonomously proposed a trajectory, and the user expressed their contentment to the machine. By moving their left or they right arm, the corresponding brain signals were recorded and classified in order to convey to the robot satisfaction or dissatisfaction respectively (Bustamante, 2018).

This collaborative framework is called shared control, and it has been recently explored in the domain of brain-robot interfaces. The infrastructure for this pilot project worked fine, and opened the door for interesting directions in research. However, it also evidenced several technical challenges that such a shared control approach would bring for researchers. Examples are robot skill learning, computer vision, human-robot interfaces and pipelines for classification of brain signals. As a follow-up to the project, our motivation was on the interface between the subject and the machine. Our hypothesis is that information-theoretically efficient approaches in BMI (refer to Omar et al., 2010) could benefit from a controlled environment in which the visual feedback of a robotic arm is enhanced with visual cues. Such a system could be achieved by either using a real arm in augmented reality or a virtual one in VR. Since a simulated arm is much more flexible, and is not prone to crashes or technical problems, we devised the development of a VR system that works as a testbed. This was the conception of ArmSym: a tool on which researchers from the Max Planck Institute for Intelligent Systems and its partner institutions can test novel paradigms in robot control and human-robot interaction for assistive robotics. It is very important to note that the flexibility of the VR system allows for experimenting in different contexts. Three examples of domains on which ArmSym could help gathering valuable data are:

- As in our previous work, assistive robotic manipulators (ARMs) mounted on wheelchairs. These robots are aimed for patients with paralysis to gain some independence using keyboards, joysticks or (potentially) non-invasive BMIs.
- Upper limb prostheses for amputees, specially for high-level amputations like shoulder desarticulation. These prostheses need to replace the function from the lost degrees of freedom (DoF) of the human arm and hand.
- A hybrid between the last two, invasive BMIs achieve great control of ARMs. Hence it is theroretically possible to talk about wheelchair-mounted upper limb prostheses for paralyzed patients using implanted microelectrode arrays.

Information on these three domains will be further extended in Chapter 2. In the next section, I develop on the design of ArmSym and the pilot experiment

1.2 A VR system for experiments in assistive robotics

ArmSym is presented to a human using a commercial immersive head-mounted display, the HTC Vive® (Valve Corporation, Bellevue, US), widely used for gaming in VR. The infrared tracking technology from the Vive and its controllers are integrated in the design of the system. ArmSym was engineered featuring a Barrett WAM® 7

[1] A term used to denote robotic arms, usually in industrial contexts.

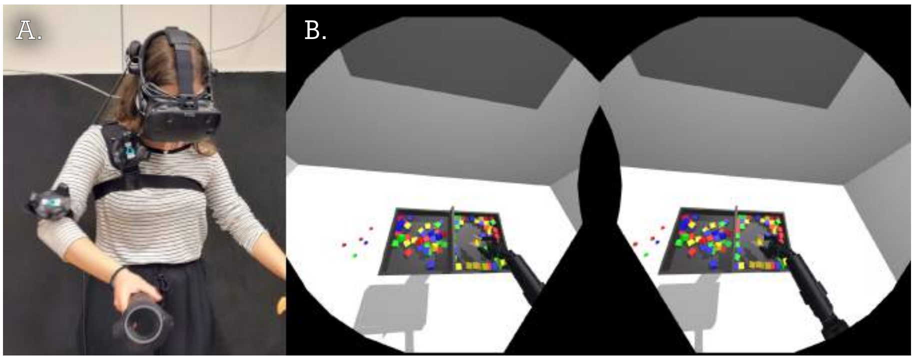

FIGURE 1.1: One participant executing a trial in ArmSym.
A. The user, controller and trackers will be explained in Chapter 3.
B. The user's view during a practice trial.

DoF commercial robotic arm (BW) and a BarrettHand®gripper. The BW model was chosen due to the notable experience of the institute with this robot, its history as a testbed in our previous work, and the yet-unexplored potential of enhancing the experience in augmented reality by interfacing ArmSym with the real robot. The task setup and the participant's first person view are shown in Figure 1.1.

ArmSym was designed with a focus on portability and ease of use, for which it adopts commercial mainstream VR technology, including Unity's gaming physics engine. The platform was developed in Unity (Unity Technologies, San Francisco, U.S.), using the well known SteamVR software development kit (SteamVR SDK, Valve Corporation, Bellevue, US). Although the kinematics of the robot are modeled using our own implementation of geometical algorithms (see Chapter 3), ArmSym makes use of Unity's physics engine for low-level tasks like rigid body interactions. Since it is designed for videogames, it is well known that this physics engine optimizes performance over accuracy, and it has been suggested on online forums that its lack of repeatability may be an issue for rigorous scientific applications (Unity Community, 2012; Unity Community, 2016). Nevertheless, the task of ArmSym is not one of scientific modelling: given that the interaction between objects looks real for the end-user, and under the hypothesis that physical imprecisions can be neglected, we suggest that this engine is suitable for this purpose. In order to test the system's interactions, specially those which use the physics engine, a pilot experiment is proposed that contextualizes ArmSym in the domain of upper-limb robotic prosthesis for high-level amputees.

Recruiting healthy right-handed subjects, we use a virtual implementation of the box and blocks test, a standardized test for manual dexterity, as our '*drosophila melanogaster*' (see Chapter 2 Section 2.3). The aim of the experiment is two-fold. First, we tested participant's execution of a timed task in different conditions within ArmSym, and compared it with the execution on the same task in the real world, in order to discuss the physics engine and the plausibility of using such a system. Second, we explored some psychological metrics for successful human-robot interaction by giving pilot questionnaires to participants.

The present manuscript is developed as follows. In Chapter 2, I present a theoretical framework, where I first explore the state of the art of sytems like ArmSym, then elaborate on the potential contexts where ArmSym could be applied, and finally observe some psychological metrics that we could use to test how participants interact with the robots. Afterwards, in Chapter 3, I describe the design process of

ArmSym. In Chapter 4 I present the methods and results of the pilot scientific study that we conducted with ArmSym. Lastly, in Chapter 5 I write some concluding remarks discussing the data, outlining some potential uses for ArmSym, and sharing ideas on BMI-ARMs and upper limb prostheses.

Chapter 2

Theoretical Framework

"While my gall-bladder is a part of me that I know exists, my leg is that and more."

O'Shaughnessy as quoted in De Vignemont, 2011

This chapter is divided into five sections. In Section 2.1, I highlight the state of the art of robotic assistive systems in VR, specially those related to upper limb prostheses. In Section 2.2 I provide a short summary of the exploratory review we conducted on assistive robotics, from both the upper limb prostheses and the BMI-powered assistive robotic manipulator perspective. In the remaining sections I explore some of the metrics that can be used to evaluate the interaction between a human and their assistive device. I explore in Section 2.3 not only performance on timed tests, but also psychological phenomena like embodiment (or perception of embodiment) and the combination of perceived ease of use, affect, and stress. Finally, in Section 2.4 I underlie the hypotheses that we test in our pilot study, which we devised from these metrics.

2.1 State of the art of assistive robots in VR

Extensive work has been done in prosthetic simulations on VR, both including or not head-mounted displays and robotic arms. Notably, Hauschild, Davoodi, and Loeb, 2007, introduced a muli-computer VR system that featured a robot arm in a head-mounted display with applications in prosthesis design and fitting, as well as invasive Brain-Machine Interfaces (BMIs). Later, Lambrecht, Pulliam, and Kirsch, 2011, argued that portability and simplicity are desirable elements for prosthesis models in VR to be used in clinical settings, and proposed and validated a simpler setup that featured a robotic commercially-available 2-DOF prosthetic arm and shutter glasses.

More recently Putrino et al., 2015, proposed a VR platform in which a 27-DOF-model of the primate arm was presented to a subject, aimed at invasive brain-machine interface studies. Wodlinger and colleagues (Wodlinger et al., 2015; Armiger et al., 2011) further presented a tetraplegic woman with a VR simulation of a robotic arm, which she controlled using an invasive BMI. In a similar way, some studies have focused on presenting the silhouette of a human arm to a subject to train control during prostheses fitting, notably Resnik et al., 2011, Nakamura et al., 2016, Muri et al., 2013, Pons et al., 2005, and Lai et al., 2017, albeit only Nakamura uses a head-mounted display. Lastly, the Target Achievement Control (TAC) test was proposed as a virtual screen-based test for pattern recognition control (Simon et al., 2011; Young et al., 2014).

To our knowledge, these systems want to mimic existing robotic prostheses (or the human arm) in order to tune design parameters, train patients for fitting procedures, test electromyographic (EMG) algorithms and, in some cases, serve as low-cost low-risk devices for experiments of control in neural interfaces. ArmSym focuses on this last purpose but deviates from former approaches: instead of aiming to mimic existing devices in prosthetics, it uses a well-known commercial robotic arm (with the possibility of using extra degrees of freedom) in order to explore the experience of participants with high-level design conditions (such as high-level trajectory control of multiple joints, or the use of artificial intelligence in robotics), without *a priori* limitations on potential patient groups, and with the intention of (portably) testing psychological phenomena such as embodiment or perceived ease of use of the apparatus (See Sections 2.3 & 2.4).

From the work reviewed, only two studies (Hauschild, Davoodi, and Loeb, 2007, & Lambrecht, Pulliam, and Kirsch, 2011) address their system as a first-person tool capable of evaluating control strategies in prostheses. Both studies implemented the box and blocks test like in our experiment presented in Chapter 4, Hauschild et al. using a simpler setup. However, they only test performance in dexterity. Their studies did not aim to evaluate user interaction. Furthermore, in these papers an important part of control is done by means of EMG, which is subject to uncontrolled noise. By targeting healthy subjects using joysticks, ArmSym is less prone to noise, and furthermore it could theoretically present noise to the participants in a controlled way for experiments on that matter.

From the studies we know, only Wodlinger et al., 2015, provides an experimental setup aimed at ARMs, in this case oriented to invasive BMIs. Their VR methods are based on previous work by Armiger et al., 2011, and feature diverse control layers and a kinematic model for a virtual John Hopkins's Modular Prosthetic Limb (Johannes et al., 2011). The system was used for calibration before experiments with the real robot, and increased the performance of the user in dexterity tests. However, no head-mounted display was used to present the robot to the participant; instead a shutter-based 3D television was used (Wodlinger et al., 2015).

We have no knowledge that any of the above studies (with the exception of Nakamura et al., 2016, albeit his control is partly done via EMG) uses a modern gaming-engineered head-mounted display. This is novel, since HTC Vive has engineered a tracking system that accurately describes in real time the position of the display, controllers and Vive Tracker® devices, and that can be used with healthy (and therefore naive) subjects to study control paradigms of ARMs. Niehorster, Li, and Lappe, 2017, studied the accuracy of the HTC Vive tracking system, and concluded that as long as tracking area remains relatively small (opposite to, for example, locomotion tasks), the device can likely be used with scientific rigor.

2.2 Neural interfaces for assistive robots

Many types of robots can fall in the category of 'assistive robots'. In the present work, only humanoid robotic arms are considered. From this category, three different applications arise, which I further explore:

- Upper limb prosthetics, i.e., devices that replace a missing limb.
- Wheelchair-mounted ARMs controlled with low-throughput interfaces.

FIGURE 2.1: Neural Interfaces that inspired ArmSym design. **A.** A high level amputee executing a dexterous task. Taken from (Miller et al., 2008). **B.** An assistive robotic manipulator, the *iARM*®robot from Assistive Innovations (*iARM*). **C.** The Brain Gate permanent interface after a craneotomy (*BrainGate*)

- Wheelchair-mounted ARMs controlled with invasive BMIs.

2.2.1 Upper limb prosthetics for high-level amputations

Research on prostheses of the upper limb varies with respect to the level of amputation of a patient, i.e., the place of the arm that was severed due to trauma or a disease. A high level means a place closer to the shoulder, and a lower level a place closer to the hand. Nowadays robot technology is being introduced in order to replace uncomfortable mechanical[1] systems that use residual movement from the shoulders. A robotic upper limb prosthesis uses surface electromyography (sEMG) from the residual muscles in order to extract a control signal. Naturally, the higher the level of the amputation, the more difficult it is to develop robotic technology: there are more natural joints (i.e., degrees of freedom) that have to be replaced, and less muscles to control the motors. In order to solve this, a surgical procedure named targetted muscle reinnervation (TMR) has been developed. During TMR, surgeons redirect residual motor nerves from the upper limb towards remaining muscles, often in the chest. These muscles serve as natural amplifiers, and constitute appropriate sEMG control inputs for a robotic prosthesis (Miller et al., 2008). As this is the kind of prosthesis approached in the pilot experiment of ArmSym, the remainder of this subsection will focus mainly on high-level prostheses.

Commercially available prostheses usually involve two degrees of freedom in the arm (elbow flexo-extension and wrist rotation) plus one on the hand (open/close). TMR control allows subject to simultaneously operate the hand and the elbow (Miller et al., 2008). A commercial device from this paper is shown in Figure 2.1A. Research in the field is intended on improving the acceptance rates of the devices. In order to do so, developments focus on three non-independent variables, as first shown by Fougner et al., 2012:

[1]With this I mean non-robotic assemblies based on a patent by David W. Dorrance in 1912: `https://patents.google.com/patent/US1042413A/en`

- The first variable is the activation profile of joints, meaning whether the control is on/off, multi-level or proportional. Commercial elbows work proportionally, while typically commercial hands work on/off (Fougner et al., 2012). Simultaneous and proportional control of prosthetic joints has been recently proposed in the literature (Fougner, Stavdahl, and Kyberd, 2014; Rehbaum et al., 2012).
- The second variable is the amount of channels taken into account. Commercial prostheses mainly use a single sEMG feature, but modern techniques in machine learning may allow to use different sEMG features and even integrate other variables like external force sensors or accelerometers, etc. State of the art research explores this multi-modal approach (Fougner et al., 2012, see references 31, 47 and 48 of that paper for more information).
- The third variable is intent interpretation: does the joint have a single function, multiple functions, or a state machine together with other joints? Research focuses around the concept of pattern recognition in sEMG signals, which means that the user controls different actions that the robot may execute in joint or task levels, and the activation is usually on/off. The main idea is that individuals generate muscle contractions that they associate with a given movement for the robot to execute (Stevens, 2014), thus rendering the prosthesis more intuitive. The alphabet of possible movements of the robot is therefore finite, and the options are mutually exclusive. However, it has been shown that it is possible to have proportional pattern recognition: the machine learning pipeline includes one classifier for the mutually exclusive actions, and one mapping or regression function that helps controlling the motors in proportional ways, maybe as force estimators (Fougner et al., 2012, refer to its reference 30 for more information).

The present work includes two different prosthetic systems, as will be explained in Chapter 3.

2.2.2 Wheelchair-mounted assistive robots

Wheelchair-mounted ARMs already exist in the market; two examples are Assistive Innovations's *iARM*®(depicted in Figure2.1B) or Kinova Technologies's Jaco®, as reviewed in Blom and Stuyt, 2017. These systems aim to help with the activities of daily living of motor-impaired patients. Control is achieved by using additional joysticks and keypads; some of them have features that make them accessible to people with fine-motor impairments (Blom and Stuyt, 2017). Current concerns in research refer to both acceptance of the technologies and reduction of costs (Blom and Stuyt, 2017). Please refer to this book for more information on development of interfaces for ARMs.

In the last few years, research in neural engineering has focused in controlling ARMs using low-throughput BMIs, which may increase the population of patients that could benefit from the robots. This has mainly been approached by using electroencephalography (EEG). Kinematic control of the robot end-effector, i.e. moving the hand in either joint or task space, has been attempted in numerous papers, notably Meng et al., 2016, Müller-Putz and Pfurtscheller, 2008, Palankar et al., 2009, Horki et al., 2011, Hortal et al., 2015, Fukuma et al., 2016 and Costa et al., 2014. The paradigms used are mainly motor imagery, steady-state visual evoked potentials

(SSVEP), and P300 potentials, although brain signals from magnetoencephalography have been explored (Fukuma et al., 2016).

Even though some of these studies have achieved a certain degree of control, my understanding is that a system like this is not very practical. The signal obtained from the EEG in any of the paradigms discussed before has very low information transfer rates, due to the fact that the user has to concentrate for long periods of time to elicit a signal (on the order of 3-5 seconds for motor imagery), and also that a tremendously low signal to noise ratio makes processing pipelines of the signal complicated. It would be much more practical, however, if control was shared between the robot and the user. This relies on the user selecting actions that the robot executes. Such a paradigm has been explored by Grigorescu et al., 2012, using SSVEP; Onose et al., 2012, using a combination between motor imagery and eye tracking; Johnson et al., 2010 & Bell et al., 2008, using P300 potentials; and by Iturrate, Montesano, and Mínguez, 2010 & Iturrate et al., 2015, using an error-related potentials as reward signals for reinforcement learning trials. All these paradigms, nevertheless, require the attention of the user in order to elicit passive or reflective potentials, and I hypothesize that using active commands might be a more efficient direction of research, as shown in the previous work section in Chapter 1. From the papers explored, only Onose et al., 2012 presents a system of this kind. Althought it has not been included in the validation experiment, we claim that ArmSym could potentially be useful to test shared control paradigms in BMI-engineered ARMs.

Lastly, it has to be noted that wereable robotic technology has also been researched. These kind of robots exceed the scope of the present work, but the reader is invited to refer to Lisi and Morimoto, 2017, for an excellent review of the technology available.

2.2.3 Invasive brain-robot interfaces

Research in invasive BMIs for robotics was first explored in primates (Velliste et al., 2008), but has recently reached tests on humans. Researchers at various US institutions have published a series of papers (Collinger et al., 2013; Wodlinger et al., 2015) that show very impressive control [2].

These systems use recordings of neurons populations to extract movement intent. Hence, it is necessary that electrodes remain in the cortical regions of the patient, which requires an implantation surgery that removes the skull. This is one of the main limitations of this technology: surgeries might be expensive and complications are dangerous, and connectors have to remain on the head of the participants (Collinger et al., 2013). An illustration of such a connector and an attached high-bandwidth cable is shown in Figure 2.1C.

Lastly, recent research has brought computer vision in order to implement shared control, which made it easier for the users to execute certain taks (Muelling et al., 2017).

2.3 In search of a metric

When new developments are usually brought in any of the neural interfaces (NIs) discussed previously, the performance of the systems is studied with timed tasks.

[2] CBS News has made public their coverage of this case-studies in 2012, and it is accessible on their Youtube channel: `https://www.youtube.com/watch?v=Z3a5u6djGnE`.

We implemented one of these timed tasks, namely the box and blocks test. However, we also would like to explore some other metrics that arise from psychological phenomena, and how that may influence the human acceptance of ARMs. In the following subsection I elaborate on the metrics that we studied.

2.3.1 The box and blocks test

The box and blocks test is a test for dexterity, whose standarization was written by Mathiowetz et al., 1985. The participant is presented with a box with two compartments separated by a partition with defined measures. The user is asked the following:

> "I want to see how quickly you can pick up one block at a time with your right (or left) hand. Carry it to the other side of the box and drop it".
>
> Mathiowetz et al., 1985

The user, seated, is asked to transfer as many blocks as possible on a limited time, originally one minute. However, different variations exist regarding to the time and the pose of the users. Studies in prosthetics conduct the test standing and in two minutes instead of one, given the difficulty for the users to pick a block (Miller et al., 2008; Lambrecht, Pulliam, and Kirsch, 2011). Modified versions of the test for healthy subjects exist, as reviewed by (Kontson et al., 2017). The users should move the blocks in different fashions, but consistently the trials stop whenever the user moves the 16th block.

2.3.2 Embodiment

The concept of embodiment of a robotic limb is arguably one of the most discussed ones in the literature of prosthetics. Pilarski and Hebert, 2017, suggest that the main goal of prosthetic design should be to "*have a user fully embody their prosthetic device as their own limb*". However, research seems to focus on the concept of embodiment as in the '*illusion*' of embodiment rather than a more holistic perspective of the concept. In this subsection I explain first the illusion of embodiment, contextualized by the experiment of the rubber hand illusion. After that I further elaborate on more general definitions of embodiment. The present text is not sufficient, in the sense that it is assumed that embodiment is indeed a critical factor in device acceptance. This assumption could be debated, as to our knowledge no correlation has been established between perceptions of embodiment and acceptance rates of prosthetic limbs. Nevertheless, such a debate is out of scope for the present manuscript, and for the remaining part of the thesis I will assume that embodiment is an important factor *per se* in device acceptance.

The rubber hand and the motorized rubber hand illusion

The reader might be familiar with the rubber hand illusion, presented first on a paper by Botvinick and Cohen, 1998. A participant sat down with their left arm being hidden from their view, observing instead an anthropomorphic rubber hand. Both hands, rubber and real, would be stroked with a brush simultaneously. This causes a strong illusion in which the participant seemed to feel the touch on the rubber hand instead of on the hidden real arm. Moreover, subjects tended to answer very positively the question: "*I felt as if the rubber hand were my hand*" .

This experiment has successfully been replicated in the case of amputees by simultaneously stroking the rubber hand and the stump, which elicited the illusion of sensing touch on the artificial hand rather than on the stump itself (Ehrsson et al., 2008). This illusion was further reproduced with a robotic hand that subjects controlled via sEMG signals (Rosén et al., 2009). Interestingly, in this experiment the users reported feeling the illusion even in trials where cutaneous touch was absent, i.e., they reported they perceived embodiment just when their motor intentions matched their visual feedback. The authors warn, however, that answers to questionnaires about ownership could have been biased by a strong sense of agency, defined as "*the experience that the person is the author of the action*" (Rosén et al., 2009). In any case, the illusion was much stronger in the presence of cutaneous touch. Marasco et al., 2011, builds over this construct to provide a closed-loop touch system for TMR patients.

The study of Rosén et al., 2009, provides us with some interesting questions concerning the perception of embodiment. First, what is the relation between agency and embodiment, if there is one? Second, could the perception of embodiment be enlarged, such that it is just not a temporary illusion? The answers for these questions remain open, and our experiment in in Chapter 4 does not aim to get a full answer, but rather to explore pilot ideas and hypotheses. Next, I will have a further look into into a formal definition of embodiment and perception of embodiment.

A working definition for embodiment

As Longo et al., 2008, accounts for, the importance of the concept of embodiment in psychological research "*has not been matched by theoretical clarity about what embodiment is or what involves*". Definitions and concepts reach the philosophical debate about the self. From the traditional debate of "*are we body and soul, or just bodies?*" (i.e., the monist v.s. dualist debate, Kagan, 2007), an ontological question arises: "*Am I a body or do I own a body?*" (De Vignemont, 2011).

For the remaining of this manuscript, I shall adopt the following definition of embodiment:

> "Embodiment: E is embodied if and only if some properties of E are processed in the same way as the properties of ones body".
>
> De Vignemont, 2011

De Vignemont further makes a distinction between embodiment and the *'sense of'* embodiment, where the first one refers to a type of information processing, and the second one to the associated phenomenology (De Vignemont, 2011), a concept that I will call *perception of embodiment*.

This perception of embodiment is consistent with a previous definition of Longo et al., 2008, which integrated in the concept the feelings of body ownership, location and agency. These three components are particularly important for us, and we will discuss them in the discussion of the pilot experiment presented in Chapter 5 in Section 5.1.

2.3.3 Percived Ease of use

In a very interesting paper, Venkatesh, 2000, studies the concept of perceived ease of use, which influences the acceptance and usage of information technologies. To our knowledge, nobody has studied these kinds of behaviours with ARMs, neither in prostheses nor in wheelchair-mounted robots. This is therefore an attractive domain to explore.

Venkatesh proposes a model with several anchors that determine perceptions about the use of a new system:

- Internal control, which relates to self-efficacy at doing tasks.
- External control , which refers to how the system facilitates actions to the user.
- Intrinsic motivation, which is an interesting subject of study on itself, as it refers to the motivation of the users to use the system. As an example, two hypothetical questions are: Would reports about motivation vary between healthy and impaired users, if we ask the former population whether or not they would use a prosthesis if they had an amputation? Would motivation reports vary with *a posteriori* accounts on control?
- Computer anxiety, which contains the emotional attitude to computer systems, and could be contextualized as robot anxiety.

Venkatesh proposes a questionnaire to measure all these anchors. A modified version of it was introduced in the pilot experiment.

2.3.4 Stress and affect

The measurement of stress is interesting in order to test participants's frustration while executing certain timed tasks. A simple way of assessing stress is to use a visual analogoue scale, which is a simple line of 100 mm with endpoints labelled as 'none' and 'as bad as it could be' (Lesage, Berjot, and Deschamps, 2012). This reference showed that this simple questionnaire is able to highlight differences between two groups, and it is easily implementable in virtual reality. A more robust way of measuring stress is to use a biosignal, such as pulse oximetry or galvanic response.

The last metric we would like to introduce is affect, both in positive and negative connotations.Watson, Clark, and Tellegen, 1988, define positive affect (PA) as "*the extent to which a person feels enthusiastic, active and alert*", and negative affect (NA) as "*subjective distress and unpleasurable engagement that subsumes a variety of aversive mood states*". The authors develop a questionnaire that measures these quantities which, in principle, are independent from each other. We hypothesize that control in the prostheses may introduce changes in either positive or negative affect.

2.4 Pilot experiment - hypotheses

The idea of the pilot experiment presented in Chapter 4 is two-fold. First, we want to test the system, evaluate the performance of the users, and see if this performance correlates with real world performance. Second, we want to test the psychological metrics we introduced in this chapter. In order to do this, we formulated an experiment in which the user has two different degrees of control over an upper limb prosthesis in the ArmSym environment; one of them is high control, the other is low control. Details on these two degrees of control will be introduced on the next chapter.

The following list are a summary of the hypothesis we want to test in the pilot experiment:

- **H1:** The timed test in the ArmSym environment is satisfactory in the sense that:

  a) The users can perform the test in many trials with different degrees of control without many glitches and in-game inconsistencies.
  b) The participants display a learning curve, and it relates to the learning curve in the real world test.
  c) Assuming perfect control of the prosthesis in ArmSym, the results of timed tasks (meaning the rate of blocks the users transfer) in VR are comparable with the results of timed tasks with a real box.

- **H2:** In the absence of realistic cutaneous touch, induced by touching the blocks, and afferent information within VR, controlling a prosthesis nevertheless creates a perception of embodiment that:

  a) Appears without regard of the level of control the users exert over the prosthesis.
  b) Has different degrees of intensity, which correlate with the degree of control the users exert over the prosthesis.

- **H3:** The degree of control influences all of the different anchors of perceived ease of use, with higher control yielding higher perceived ease of use.

- **H4:** The degree of control inversely correlates with the degree of stress the users show during the execution of timed tasks.

- **H5:** The degree of control positively correlates with the degree of positive affect the users gain during the execution of timed tasks and negatively correlates with the degree of negative affect.

The hypothesis for possitive and negative affect was not tested, since the analysis for this questionnaire is out of the scope of the present manuscript.

Chapter 3

ArmSym design and development

In the present chapter I share the components of ArmSym as a VR application. In Section 3.1 I underline the hardware and software components of the system. In Section 3.2 I describe our physical models for the robot, including the two control modes presented further on our pilot experiment. Finally, in Section 3.3 briefly describes the scenes we implemented in Unity as part of our application.

3.1 Hardware and Software

We presented ArmSym to participants using a head-mounted display, the HTC Vive® (Valve Corporation, Bellevue, US). This device uses two infrared cameras in order to track the position of the head-mounted display and controllers. Due to a persisting jittery problem in the experimental room, the experiments were run with just one camera. This reduced setup still allows for depth measurements, and our technical understanding is that the only potential problem would have been eventual increased occlusion.

The virtual reality environment was developed in Unity (Unity Technologies, San Francisco, U.S.). Scripting was written in C#. The dependencies we used are:

- SteamVR, a well known software developement kit for the HTC Vive in Unity (SteamVR SDK, Valve Corporation, Bellevue, US).
- MathNet.Numerics, a C# library that includes linear algebra support [1].
- VRTK, a toolkit for VR objects and scripts in Unity [2].
- LSL4Unity, a toolbox that allows Unity to communicate with streams of lab streaming layer (LSL). This is a very useful platform for streaming signals, biosignals and, in our case, markers.[3].

We used Vive trackers (Valve Corporation, Bellevue, US) in order to know in real time the positions of the elbow and shoulder of every participant. Interactions in the simulated world were made using Unity's rigid body interactions, which rely on the physics engine. We decided to limit to 100 the number of blocks, given that more blocks necesarily increase the number of interactions.

Due to the project development timeline, only for half of the participants we measured the heartbeat response. Pulse oximetry was measured on the left index finger using a Nellcor ®oximeter (Medtronic, Minneapolis, US). The signal was amplified

[1] https://numerics.mathdotnet.com/

[2] https://vrtoolkit.readme.io/

[3] https://github.com/xfleckx/LSL4Unity

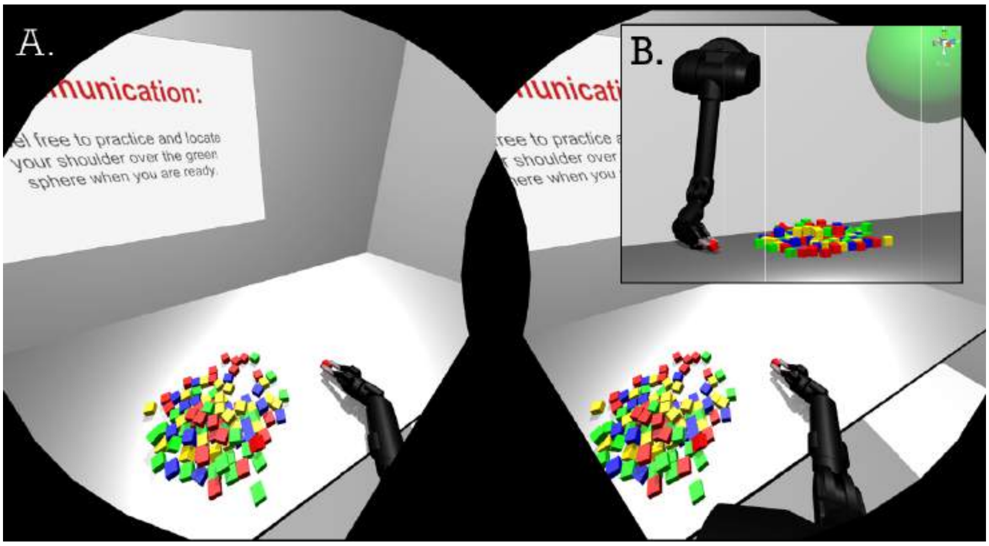

FIGURE 3.1: The robot model of ArmSym in Unity. **A.** The subject's view. **B.** A render of the whole robot during the task.

using a BrainAmp amplifier (Brain Products GmbH., Gilching, Germany). The signal was stored using OpenVibe. The data was synchronized with Unity using the plugin LSL4Unity and a server in python. We used an armrest with a variable height in order to keep the left hand of the participants as static as possible. Participants that did not have the oximeter were not given any instructions about where to place their left arm.

3.2 Control modes

ArmSym was developed featuring two control modes: In the first one, the user controlled the robot exactly as their own arm, meaning that the hand and the elbow were reflected to the robotic hand and elbow one to one. We called this inverse kinematics control (IK). In the second one, the user controlled the robot as in a real prosthesis, i.e., only with 2 degrees of freedom in the arm and one in the hand. We called this prosthesis mimicking (PM). Before I jump into details about both control modes, I will present the general framework for the robot next.

3.2.1 A model for the robot

In Figure 3.1 I show the robotic arm in Unity. First, Figure 3.1A contains the first person view that mirrors what a participant was seeing in virtual reality as they grabbed a cube. Figure 3.1 displays the full robot arm with its base floating in space on the position where the shoulder of the participant is. The robot featured in ArmSym is a Barrett WAM® (BW) 7 DoF commercial robotic arm, and a BarrettHand®gripper (BH). A 3D model from the robot pieces was obtained from Barrett and loaded into Unity. In the pilot experiment, the robot was contextualized as an upper limb prosthesis for shoulder desarticulation amputees. Therefore, the robot was presented to the user in a first person view, and the base of the robot was located on the shoulder of the participant using the Vive trackers.

The 3D model of the robot was assembled in Unity using geometrical transforms according to the denativ-hartenberg (DH) parameters. These parameters refer to a notation that accounts for the geometry of a robot and its pose once the inputs of the motors are established. The details are out of the scope of this thesis. In the need for more information, the reader is invited to refer to the excellent textbook by Craig, 2005, which explains how these transformations produce different robot poses. In a conference paper from 2017, we showed a methodology for producing such robot ensembles in an online application, albeit in MATLAB. If practical information is required, the reader is kindly invited to refer to this previous work: Bustamante et al., 2017.

Using Unity and C#, the assembly of the robot was set on every frame. This proved being an efficient model for the robot: when the assembly received an input in joint space[4], the robot effectively produced a correct end effector pose in task space[5]. This kind of model is called direct kinematics.

Hand grasping

The control of the Barrett Hand (BH) was always on/off (See Chapter 2 Section 2.2), and in-game it corresponded to the on/off trigger button of the controller of the HTC Vive. The BH was assembled without a dynamic model for its motors, i.e., there was no model of the force interactions at the moment of grasping. Nevertheless, the pieces of the hand were designed as rigid bodies, and as such interacted with the cubes in a realistic way. The problem of grasping was solved by a heuristic: every time the hand would close over a cube, this cube would become temporarily attached to the robotic hand, until it would be dropped.

3.2.2 The inverse kinematics control mode

In this control mode, participants moved the controller around space, and the hand of the robot would follow it directly. This means that the robot arm had to find the joint angles that satisfy the position and orientation of the controller with respect to the base of the robot, located on the shoulder. This type of model receives the name of inverse kinematics, hence the name we gave to the control mode (IK).

The inverse kinematics is a non-trivial geometrical problem, and its often solved with numerical methods. We decided to use an analytical model instead, formalized by Singh and Claassens, 2010. This design choice gave us freedom to optimize the performance of the code, and avoid iterative solutions that could have significantly affected the frame rate of VR. Performance in VR is vital: if the frame rate is affected by slow code, it starts producing diziness effects on the users. Therefore, we created our own implementation in C# of the out-elbow algorithm proposed by Singh and Claassens, and optimized its performance by creating pre-trial memory allocations, which reduced the garbage collection. We found that our optimized code was able to run without problems at 90 Hz, which is the refresh rate of the HTC Vive's screen. This means that on every frame the robot was able to find a solution for the joint points that satisfied the relative pose of the controller with respect to the shoulder tracker.

This solution constrains only 6 of the 7 degrees of freedom of the BW, as position and orientation of the hand can be defined by 6 independent variables. The redundancy manifold was identified by Singh and Claassens and parametrized with a single variable ϕ. In order to make the movement of the robot look realistic, we constrained ϕ in such a way that the elbow of the robot would lie over the elbow

[4]Joint space refers to the joint inputs from the robot motors

[5]Task space refers to the position and orientation of the end effector, the hand of the robot

tracker, using the azimutal angle of the elbow tracker with respect to the shoulder tracker. This heuristic proved to give a realistic impression of the robotic elbow moving as the real human one for some regions of the Cartesian space, including the one in which the table, box and blocks were located.

We show a participant executing a trial of the inverse kinematics control mode in Figure 3.2A. Notice that this participant has a pulse oximeter, and therefore she relaxes her arm on the armrest. On the figure are also shown the trackers in the shoulder and the elbow of the participant. In our model, we accounted for the offset between the physical trackers and the body joints.

3.2.3 The prosthetic mimicking control mode

Using the direct kinematics model from subsection 3.2.1, it was straightforward to develop our prosthetic mimicking control mode. This kind of control allows only for two degrees of freedom: the elbow joint (the fourth joint of the robot) and the wrist rotation joint (the fifth joint of the robot). All the other joints were constrained in anatomically correct poses. The fourth and fifth joint were constrained to a range of 120 and 180 degrees respectively.

Speed control for the two degrees of freedom was mapped from the analogous 2D joysticks of the controllers of the HTC Vive. As the base of the robot was attached to the shoulder tracker, the whole assembly would move along with the user as they moved or rotated their torso. We often found that the users used their shoulders to compensate for movements. We show a participant executing a trial of the prosthesis mimicking control mode in Figure 3.2B. Notice that the elbow tracker is not necessary. For illustrative purposes, this participant does not have a pulse oximeter, and therefore adapts the left hand to a position that gives her comfort and balance. It is important to recall that half of the oximetry participants belonged to each group.

3.2.4 The real world test

The real box and 150 blocks were manufactured according to the instructions set in the original paper by Mathiowetz et al., 1985. The cubes were painted in red, blue, green and yellow as in the example. A participant executing a trial with the test is shown in Figure 3.2C.

3.3 Game scenes

Unity 3D works with scenes in which the game designers introduce all the objects they want to present in VR. Our main scene was the box and blocks test scene, which I introduce next. After that, I present some other scenes that helped the experiment progress in a natural way.

3.3.1 The box and blocks test scene

We stated that the box and blocks test is our *'drosophila melanogaster'* for the pilot experiment. We show the in-game view of this scene in Figure 3.3. The cubes were painted in red, blue, green and yellow as in the real world setup. The right compartment of the box was filled with 100 cubes instead of 150 for performance reasons. Nevertheless, there was an algorithm that filled the right compartment again if the number of cubes went under 10. No participant achieved a score that high during our short trials. All the in-game questionnaires were adapted in this scene.

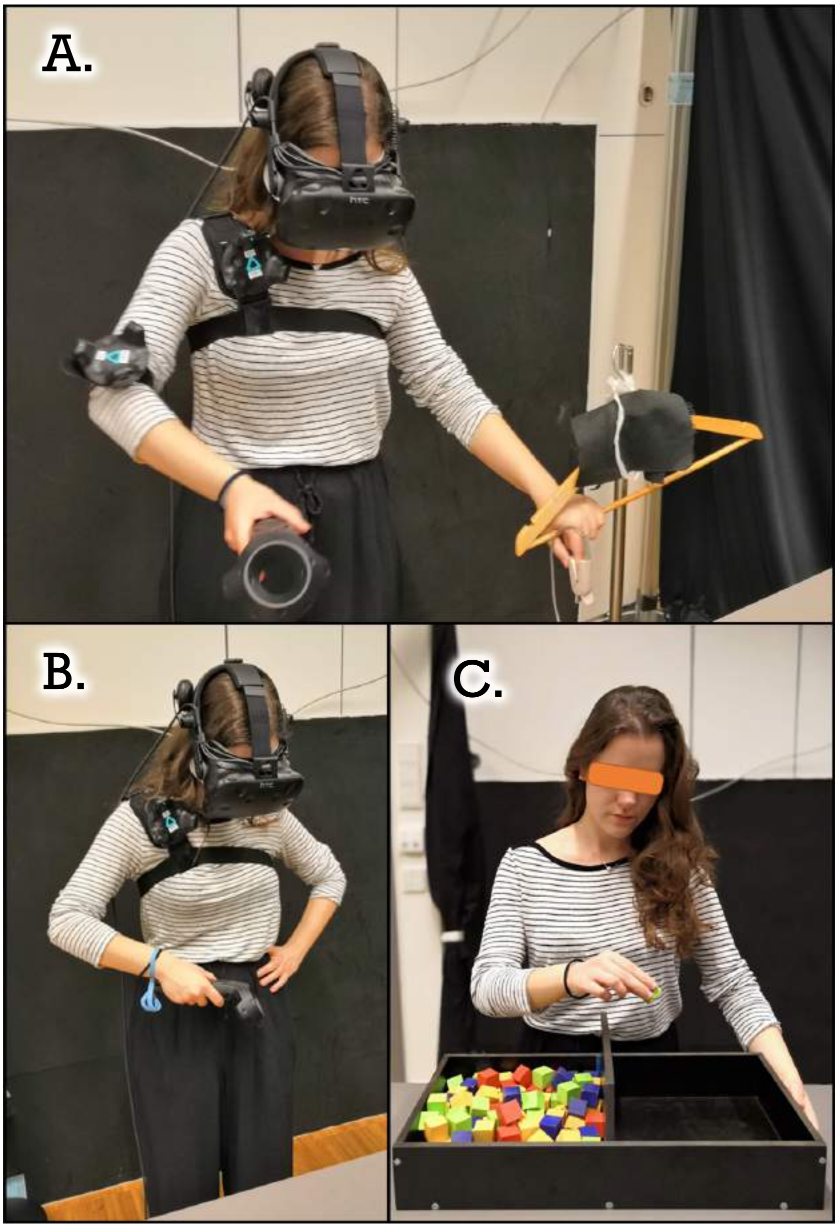

FIGURE 3.2: A participant in the setup of the pilot experiment. **A.** During an inverse kinematics trial, wearing a shoulder tracker, an elbow tracker, and a pulse oximeter. **B.** Subjects from the prosthesis mimicking group did not have to wear an elbow tracker, and half of the participants ran the experiment without using oximetry. **C.** The real box and blocks test, standing as in VR.

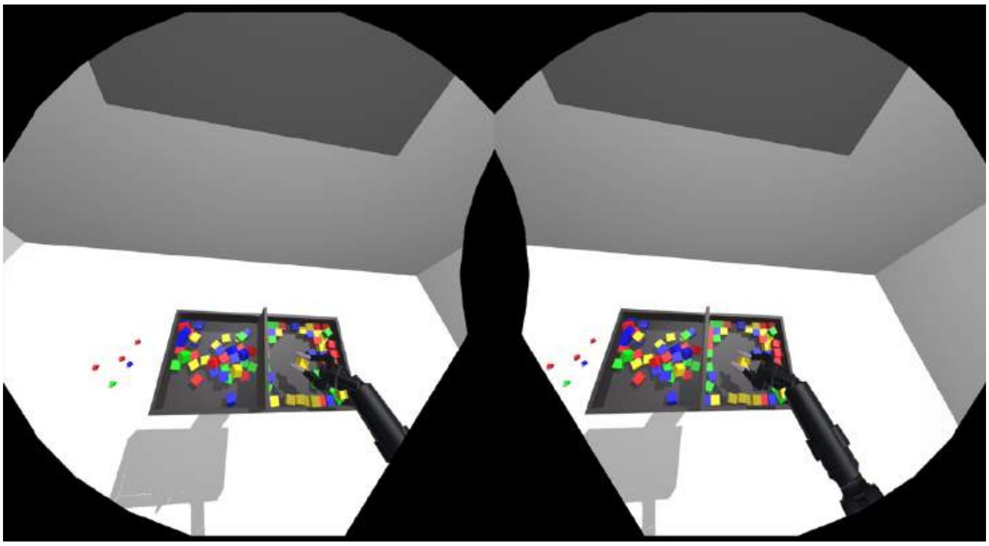

FIGURE 3.3: The virtual box and blocks test scene.

3.3.2 Other scenes

- A configuration scene, only accessible to the experimenter. The experimenter indexed all the information regarding the trials, questionnaires and participant data (age, pseudo-anonymous identifier, gender, among others).
- A calibration scene, where the length of the arm of the user would be measured. The length of the robot geometry was shrunken in such a way that the maximally extended arm had roughly the same length in both VR and the real world. This scene also recorded data on the height of the shoulder of the participant.
- A practice scene, where the user could learn the control over the robot. Please see the next chapter for more information.
- A pause scene, in which the participants were allowed to take breaks periodically for 2 minutes (the order is underlined in the next chapter). The pause scene displayed a timer and a 'continue' button that users could press when they were ready. The 2-minute deadline was not strictly enforced.

Chapter 4

Pilot study for validation of the system

As we discussed in Chapter 2 Section 2.4, we wanted to formulate an experiment to validate the system and test some of the psychological hypotheses we formulated. In order to do this, an experiment had to be developed such that:

- different control levels of the prosthesis would be evaluated.
- data on performance would be stored.
- diverse questionnaires would be asked to participants, tailored for the metrics that we intended to measure.

I describe the experiment and revisit the metrics and the hypotheses in Section 4.1. 27 subjects participated in our experiment, all conducting the box and blocks test using VR. The results are presented in Section 4.2. The discussion, along with some comments on the future of ArmSym and ideas I consider interesting, are available in the Discussion, in Chapter 5.

4.1 Methods

4.1.1 Experiment

We recruited 27 healthy right-handed subjects for the experiment. From these, the data of three subjects was rejected: the questions were modified after running their experiments, rendering their data incomparable; data from participant S06 was also rejected due to an evident miscalibration. Therefore, the data from 24 subjects was collected and presented. A condition for participants in the experiment was not to wear glasses, as it is problematic to fit big frames in the HTC Vive. This rule was relaxed for two subjects who provided proof of having frames small enough to fit in the device. Participants signed an informed consent form.

The robot was presented to subjects in a first person view, meaning that the base of the robotic arm was located on their right shoulder, resembling a high-level robotic prostheses. The 3D avatar of the robot was shrunken in a calibration procedure such that the robot was approximately fully extended when the users had their arms fully extended. Without loss of generality, a trial consisted of one run of the box and blocks test, with the subject standing instead of sitting down.

The subjects were divided in two groups, accounting to two conditions:

- Condition Prosthesis Mimicking (PM): This condition was intended to reply real life conditions of upper limb prosthetic amputees, using a 3-DOF control scheme in joint space inspired by the experiment of Miller et al., 2008: The user controlled only elbow flexion and extension (DOF 1), wrist rotation (DOF 2) and hand open and close (DOF3) of the robot. DOFs 1 and 2 were moved using proportional speed control mapped from the HTC Vive's controller analogous joysticks. The control of the joints was allowed in a simultaneous way.

- Condition Inverse Kinematics (IK): The position and orientation of the controller of the HTC Vive relative to a tracker on the shoulder was mapped one to one to the robot's end effector position and orientation, and the on/off gripper was opened by holding the gripper function of the Vive Controller. This condition already constrained 6 of the 7 degrees of freedom of the Barrett WAM® robotic arm. The last DoF was constrained via the elbow tracker, which was mapped as the relative position of the elbow to the shoulder.

For technical details of both control paradigms, please refer to Chapter 3 Section 3.2.

ArmSym Part

Participants with the inverse kinematics (IK thereafter) ran 20 trials of one minute, while participants with prosthesis mimicking (PM) ran 10 trials of two minutes. The reason for the imbalance is that it indeed takes a long time for PM participants to move a cube from one compartment to the other, but two minutes is rather long and introduces tiredness effects for the IK participants. Therefore, we designed the experiment in such a way that all participants would have the same *exposure time* to the robot. The box was filled with 100 cubes, not 150 like the real box in order to guarantee a high frame rate in VR.

Participants were allowed to have a practice trial before they started the experiment. The length of the practice trial was left to their judgment. They were instructed to start the experiment *once they felt they had control over the robot*. This practice trial was implemented due to the fact that PM participants require a lot of time to get accustomed to control, and we aim to mitigate the learning effects. By introducing the same prctice trial for the IK subjects, we believe that this learning was blocked. This practice trial included a number of blocks within a table, but did not include the actual box and blocks test, for which we hypothesize that the users learnt the control but did not learn the task.

Subjects also were permitted to have a 2 minute pause after 4 minutes of exposition, that is 4 IK trials or 2 PM trials. The subjects were invited to take out the headset if they felt they needed to during the pauses. The participants were prompted to return to the game as they pleased, and the 2 minute pause was not strictly enforced, specially with subjects who had light dizziness or soft levels of sweating. In order to reduce tiredness effects and increase motivation, participants were informed that their fourth break was their last.

Real part

All the subjects executed 10 trials of a real world box and blocks test. For practical purposes, the time metric chosen for this test was the time for the 16th block instead of the number of blocks in one minute. This would be a hybrid between different versions of the box and blocks test as referenced by Kontson et al., 2017. The subjects were standing, and the height of the real world table was calibrated such that it would match the one in VR, $85 \pm 3cm$. The experiment was performed in such a way that each participant would finish 10 valid trials. If one trial was to be rendered invalid, it would be crossed and started again. In order to account for their level of tiredness, participants were briefed after nine valid trials that they had only one to go. The following were the reasons to cancel a trial:

- The subject helped theirself with their left hand.
- The subject did not cross the partition with all their fingertips on the majority of the blocks.
- The experimenter miscounted.

In order to block for learning effects between the real box and the virtual one, half of the experiments for each condition conducted first the trials of the real part and the other half conducted first the trials of the virtual part.

Lastly, it must be mentioned that the real box was filled with 150 cubes, as is the standard in the literature (Mathiowetz et al., 1985).

4.1.2 Hypotheses and questionnaires

In the present section, the hypotheses expressed in the previous chapters are rewritten in a more precise way. Unless explicitly expressed, all the questionnaires are asked in first person and use a 7-point Likert scale.

Performance

The performance metric of the box and blocks test is the number of blocks that the user can transfer between compartments during a fixed time period. This metric was converted to the equivalent in seconds/block. During two minute trials, amputees that underwent TMR have been found to transfer between 12 and 20 blocks on average, improving from 3 to 10 blocks before surgery (Miller et al., 2008). Using Lambrecht & colleagues's virtual reality setup, 3 sequential and 3 synchronous control healthy subjects using EMG managed to move between 5 and 8 blocks on average (Lambrecht, Pulliam, and Kirsch, 2011). As a reference for our real box and blocks, Kontson et. al report that healthy subjects transport on a median of 16 blocks in 15 seconds (Kontson et al., 2017). Our hypotheses are listed next:

> ***Hypothesis 1***: *The timed test in the ArmSym environment is satisfactory in the sense that:*
>
> a) *The users can perform the test in 10 or 20 trials with their assigned control mode without many glitches and in-game inconsistencies.*
> b) *The participants display a learning curve, and it relates to the learning curve in the real world test.*
> c) *The results of timed tasks (meaning the rate of blocks the users transfer) in IK participants are comparable with their results of timed tasks with a real box, on rates similar to the one proposed by Kontson.*
> d) *The result of timed tasks in PM participants approach the rates from the studies of Miller and Lambrecht.*

Perception of embodiment

Our pilot questionnaire on the perception of embodiment is a shortened version of the one from Rosén et al., 2009. Since those questions were developed for experiments with the rubber hand illusion, we dropped out the questions that involved the mislocalization of the brush. We were left with only one embodiment question and two control questions, that according to our reference control for compliance, suggestibility and placebo effect (Rosén et al., 2009):

- Question of perceived embodiment:
  I felt like the robot was my arm.

- Control question 1:
  I felt like if I had three arms.

- Control question 2:
  The robot started to change shape, color and appearance, and started to look like my arm.

The reader will notice that we replaced the word '*hand*' with '*arm*', as in the referenced paper they use a robotic hand instead of a full arm (Rosén et al., 2009). This choice will be further discussed in Chapter 5. To these questions, one more was added that was intended to address the difference between the two control modes:

- Control question 0:
  I felt like the robot was moving like my arm.

If the inverse kinematics paradigm worked correctly, we hypothesize that this question would be very useful to separate the expected perception of real-life control correspondence between the two levels of control.

The questions were measured a total of five times in the experiment, once every four minutes of exposition and always at the end of a trial. This was timed exactly in the middle of the pauses. Therefore:

- For IK participants, the embodiment questionnaire was launched at the end of trials 2, 6, 10, 14 and 18. The pauses happened at the end of trials 4, 8, 12 and 16.

- For PM participants, the embodiment questionnaire was launched at the end of trials 1, 3, 5, 7 and 9. The pauses happened at the end of trials 2, 4, 6 and 8.

By timing the questionnaires in this way, we can claim that all participants had a similar exposition time to the box and blocks test in VR, and hence the measurements are comparable between conditions. The questions were asked on a fixed order: Control question 0, Control question 1, Question of perceived embodiment and Control question 2. Our hypotheses are detailed next:

> ***Hypothesis 2**: In the absence of realistic cutaneous touch of the blocks and afferent information within VR, controlling a prosthesis nevertheless creates a perception of embodiment that:*
>
> a) *Appears in both levels of control, for which all participants tend to answer the question of perceived embodiment in a positive way of the Likert scale regardless of their group.*

b) *Has different degrees of intensity correlated with control, for which the IK participants would have a significantly higher effect than the PM participants.*

c) *The control questions 1 & 2 are consistently rejected by both groups.*

d) *The control questions 0 discriminates the two control groups significantly, such that IK participants answer on the positive side of the Linkert scale and PM on the negative side.*

Perceived ease of use

We formulated a questionnaire based on the proposed model of technology acceptance developed by Venkatesh, 2000. Some of the questions were removed, as they were developed explicitly for computer software in job-related applications.

We introduced questions in order to test the anchors of 'perceived ease of use' (PEU): 'internal control' (IC), 'external control' (EC), 'computer anxiety' (CA) and 'perceived voluntariness of use' (PVU). The questions were asked once after the VR experience was over, together with the PANAS questionnaire explained later in this chapter. Some questions, PEU-2, PEU-3, PEU-4 and EC-1, were also asked at the end of the real box and blocks test, but their answers will be displayed only for visual reference. The questionnaire, as adapted from Venkatesh, 2000, is:

- Perceived ease of use:
  1- My interaction with the robot is clear and understandable.
  2- Executing the test with (the robot/my arm) requires a lot of my mental effort.
  3- I find (the robot/the test) to be easy to (use/conduct).
  4- I find it easy to get (the robot/my arm) to do what I want to do.
- Internal Control:
  1- I could move the robot without receiving any instructions.
- External Control:
  1- I have control over using (the robot/my arm).
  2- I have the necessary knowledge to use the robot.
- Computer Anxiety:
  1- Robots do not scare me at all.
  2- Working with a robot makes me nervous.
  3- I would feel better if the robot looked like a human arm.
- Perceived voluntariness of use in real life:
  1- I would use a robotic arm as an assistant for daily activities, even when my arms are intact.
- Perceived voluntariness of use in case of an amputation:
  1- I would use a robotic arm as an assistant for daily activities, if I had an amputation over the level of my shoulders.

We added the question CA3, since experiments in human-robot interaction traditionally have studied how the antropomorphism affects robotic device acceptance, which appears to be an important factor in user's desire to work with robots (Geoffrey Louie, Mohamed, and Nejat, 2017). We also added PVU questions and divided them in two independent parts, as the voluntariness of use after an amputation would not necessarily correlate with the voluntariness of use in daily activities for healthy subjects. By asking the two of them, we forced participants to indeed believe themselves in a situation of upper limb amputation.

The answers to questions whose formulation is negative (e.g.,Robots do not scare me at all) was inverted. For each participant, the answers to all the questions for each anchor were averaged, obtaining one value between 1 and 7 for each item. The hypothesis we formulated is the following:

> ***Hypothesis 3****: The degree of control heavily influences the perceived ease of use of the robotic device, such that there is a significant difference in the measurements for PEU and all of its anchors between the two groups, and being the inverse kinematics robot more easy to use.*

Visual Analogue Scale for stress

We implemented the Visual Analogue Scale (VAS) for stress as proposed by Lesage, Berjot, and Deschamps, 2012. Five measurements took place during the VR experience. The first one (VAS-0) appeared right after the calibration session, before the practice trial. The four remaining measurements (VAS - 1-4) appeared together with the embodiment questionnaire described previously. Always the VAS was presented to the user before the control question 0 for embodiment.

The VAS used an in-game slider developed in Unity. The slider had endpoints labelled as 'none' and 'as bad as it could be', which were translated to a real line as 0 and 100 respectively. The user would answer with the controller the following question:

> "Indicate on this slide how stressed you feel right now".

The hypothesis we formulated for the VAS is the following:

> ***Hypothesis 4****: Participants from the inverse kinematics group report significantly less stress than the participants from the prosthesis mimicking group in all the measurements except for the first one, after calibration.*

Pulse oximetry

Pulse oximetry as a stress measurement was introduced for the second block of participants. Therefore, half of the participants have pulse data recorded. Due to the signal processing requirements and the availability of time, this data has been stored but will not yet be presented. The analysis and results will be out of the scope of the present manuscript.

Positive and negative affect

The positive and negative affect questionnaire from Watson, Clark, and Tellegen, 1988, was introduced for 20 participants in total as an after-game questionnaire. They were asked to evaluate 20 categories that provide effective measurements for positive and negative affect, according to Watson & colleagues. This questionnaire was asked three times: Once after the participant just arrived, once after they finished the VR part of the experiment, and once after they finished the real box part of the experiment.

The questionnaire would read:

> "The goal of these questions is to evaluate your feelings and emotions. Please read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you feel this way **right now**, that is, **at the present moment**". (Originally taken from (Watson, Clark, and Tellegen, 1988))

For the first measurement, i.e., when the subject arrived, the last sentence was replaced for "Indicate to what extent you feel this way **today**". The subjects were then presented with a scale between 1 and 5, where 1 is 'very slightly or not at all', 2 is 'a little', 3 is 'moderately', 4 is 'quite a bit' and 5 is 'extremely'. The 20 items they were asked to evaluate between 1 and 5 were:

> interested, distressed, excited, upset, strong, guilty, scared, hostile, enthusiastic, proud, irritable, alert, ashamed, inspired, nervous, determined, attentive, jittery, active, afraid.

Offline, the score for the possitive affect items (interested, excited, etc.) and the negative affect items (distressed, upset, guilty, etc.) was sumed to produce a PA and a NA score respectively. We therefore had three different measurements of a PA and NA score during the whole experiment.

Only 20 subjects participated in the PANAS questionnaire. Stronger statistical tests are necessary because we have a reduced and IK/PM unbalanced set of participants. Therefore, the analysis of the PANAS data is out of the scope of the present manuscript.

4.2 Results

The experiment was run with 24 participants. S03, from prosthesis mimicking, ran only 8 out of 10 trials. Therefore, and in order to keep a great average, only the measurements 1-4 for embodiment and 0-4 for the VAS were analized. All subjects answered the VAS, perceived embodiment and PEU questions. Our four hypothesis were tested, yielding the following results:

4.2.1 Hypothesis 1 - Performance

The performance results are shown in Figure 4.1 for both control modes and the real box. In the plot I display also the results from other studies: For amputee studies, I display the mean time of the synchronous control from Lambrecht, Pulliam, and Kirsch, 2011, and the approximated mean times for real world amputees of pre-TMR (b) and post-TMR (a) from shoulder desarticulation subjects in Miller et al., 2008. For healthy subject studies, I plot the approximate median from the extrapolated data from Kontson et al., 2017, and the grand-mean from the original study by Mathiowetz et al., 1985.

In Tables 4.1 and 4.2 I show for every participant the correlation between IK and real box learning curves on the first 9 trials, using the full IK trial score. I exclude trial 10 since both real box and PM participants knew it was their last trial, which may influence the correlation[1]. On Figure 4.2 I show the best time for the sixteenth block (when available, since some times it was not. I explain in Chapter 5 the reason for this) on the inverse kinematics in comparison with the real box.

In the next subsection, I display the results on the psychological metrics.

[1]The p value displayed was obtained with scipy's pearsonr, which indicates the "probability of an uncorrelated system producing datasets with such a correlation". *scipy.stats.pearsonr* .

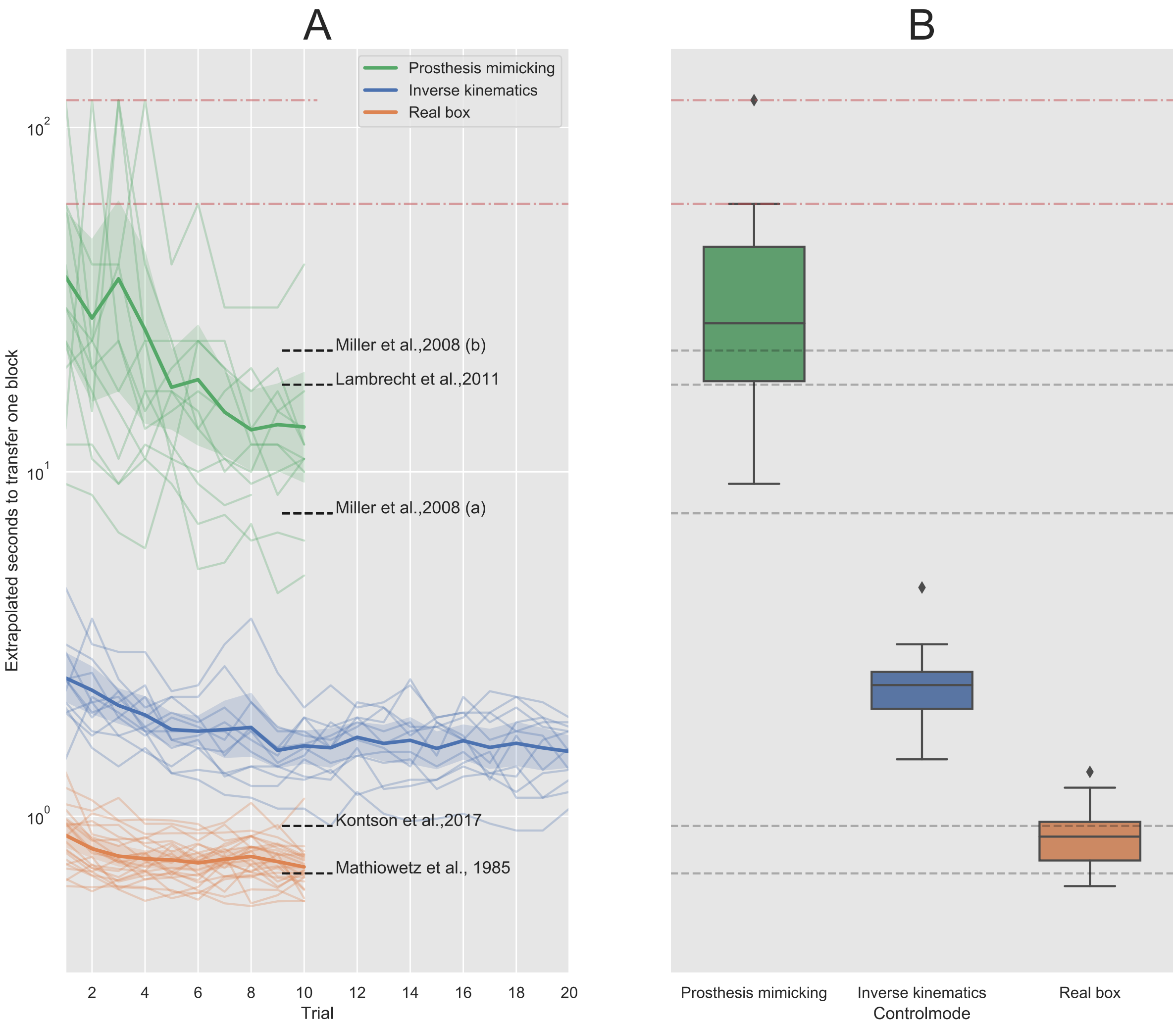

FIGURE 4.1: **A.** Learning curves of all subjects during the execution of tasks in VR and in the real world. For the Inverse Kinematics, the full trial score instead of the time for the sixteenth block was used. The red lines are 60 and 120 seconds per block. Shaded is the 95% confidence interval for the mean. **B.** The distributions for the first trial only.

TABLE 4.1: Correlation between the blocks per second scores for the first 9 trials in prosthesis mimicking vs in the real box.

Participant name	Pearson correlation	p value	Significance
S01	0.18	0.6371	ns
S03	0.46	0.2547	ns
S05	0.33	0.3864	ns
S07	0.7	0.0355	*
S09	-0.29	0.4427	ns
S11	-0.01	0.9866	ns
S16	0.05	0.9082	ns
S18	0.58	0.1033	ns
S20	-0.02	0.9593	ns
S22	0.72	0.0294	*
S24	0.89	0.0014	**
S26	0.34	0.3721	ns

TABLE 4.2: Correlation between the blocks per second scores for the first 9 trials in inverse kinematics vs in the real box.

Participant name	Pearson correlation	p value	Significance
S08	0.4	0.291	ns
S10	0.4	0.287	ns
S12	0.04	0.9165	ns
S13	0.41	0.2695	ns
S14	0.72	0.0298	*
S15	0.89	0.0013	**
S17	-0.14	0.7214	ns
S19	0.2	0.6079	ns
S21	0.4	0.2917	ns
S23	0.85	0.0037	**
S25	0.45	0.2242	ns
S27	0.75	0.019	*

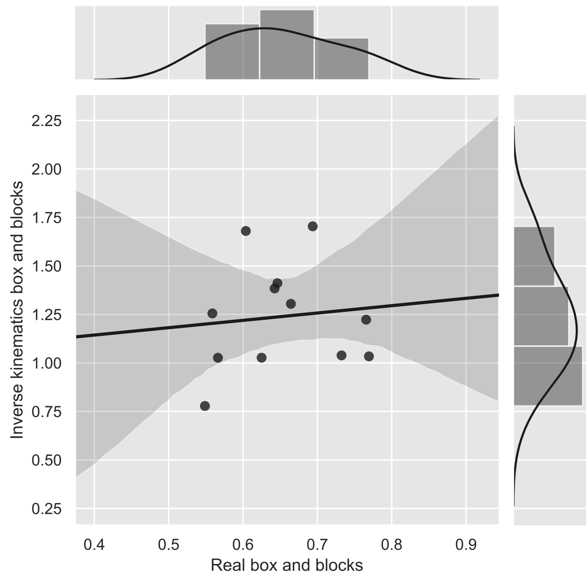

FIGURE 4.2: Comparison of the lowest amount of time in which the Inverse Kinematics subjects could move 16 blocks in the Real and the VR test. The trials in which the 16th block's time is not clear were not taken into account. The scores were divided by 16 in order to be comparable with Figure 4.1. Drawn is a regression line and a 95% confidence interval for that regression.

4.2.2 Hypothesis 2 - Perception of embodiment

The results for the first four measurements for embodiment are shown in Figure 4.3. The statistical test we used is a two-sided t-test. From the figure, it can be shown that:

- The Control questions 1 (I felt like if I had three arms) & 2 (The robot started to change shape, color and appearance, and started to look like my arm) were answered strictly negatively and there were no significant differences between groups.
- The control question 0, which accounted for agency, was responded strictly positive for the inverse kinematics group and almost always negatively for the prosthesis mimicking group, yielding significant differences in all but the third measurement .
- In the perceived embodiment question 'I felt like the robot was my arm' we observed that the inverse kinematics group answered a consistent mild positive response, while the prosthesis mimicking group responded consistently negatively, and there is a significant difference between the two groups in the four measurements.

4.2.3 Hypothesis 3 - Perceived ease of use

The results for the PEU measurements are shown in Figure 4.4. The statistical test we used is a two-sided Welchs t-test, which does not assume equal variances. From the figure, it can be seen that:

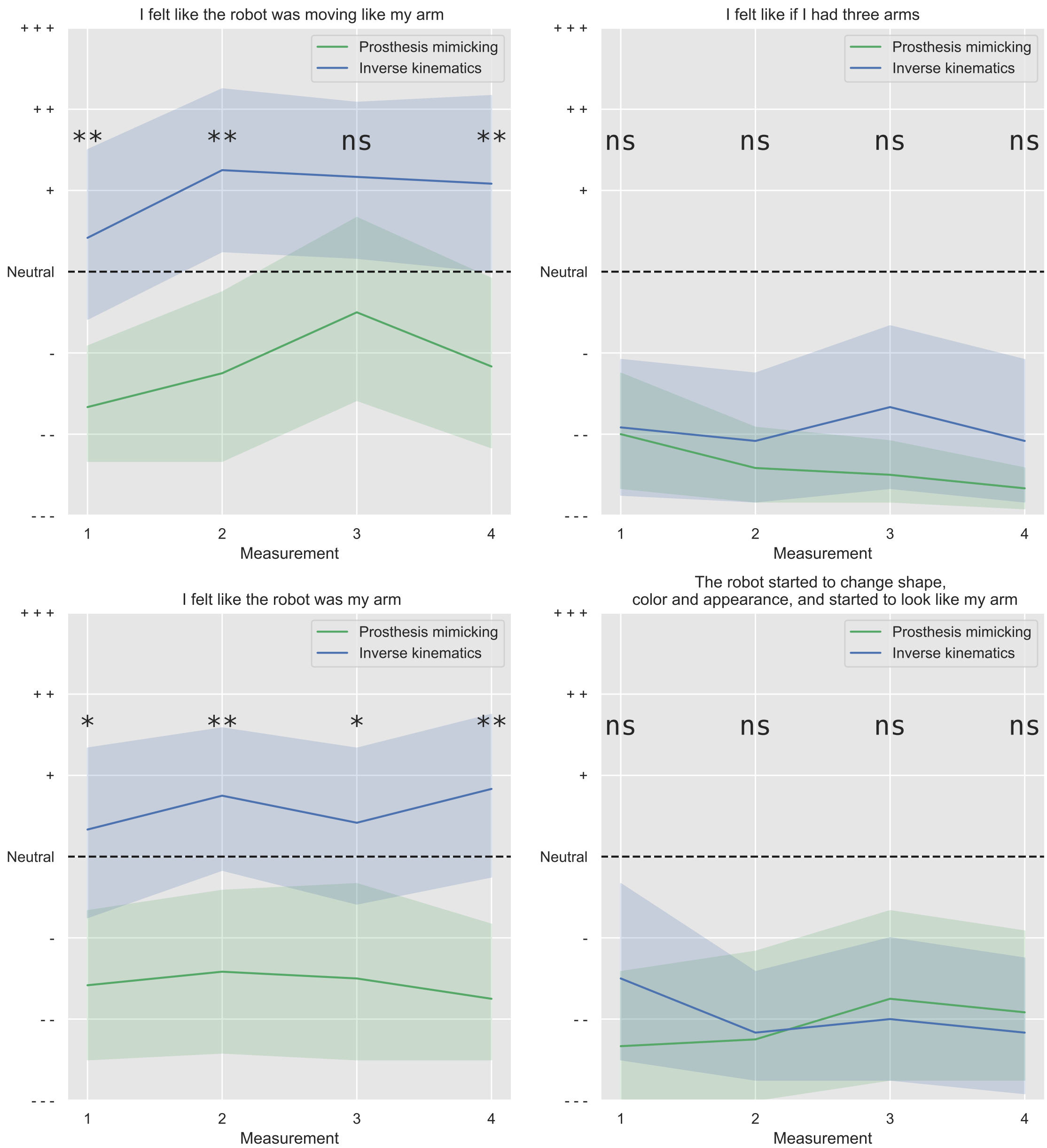

FIGURE 4.3: Answer to the embodiment questions. Shaded is the 95% confidence interval for the mean.

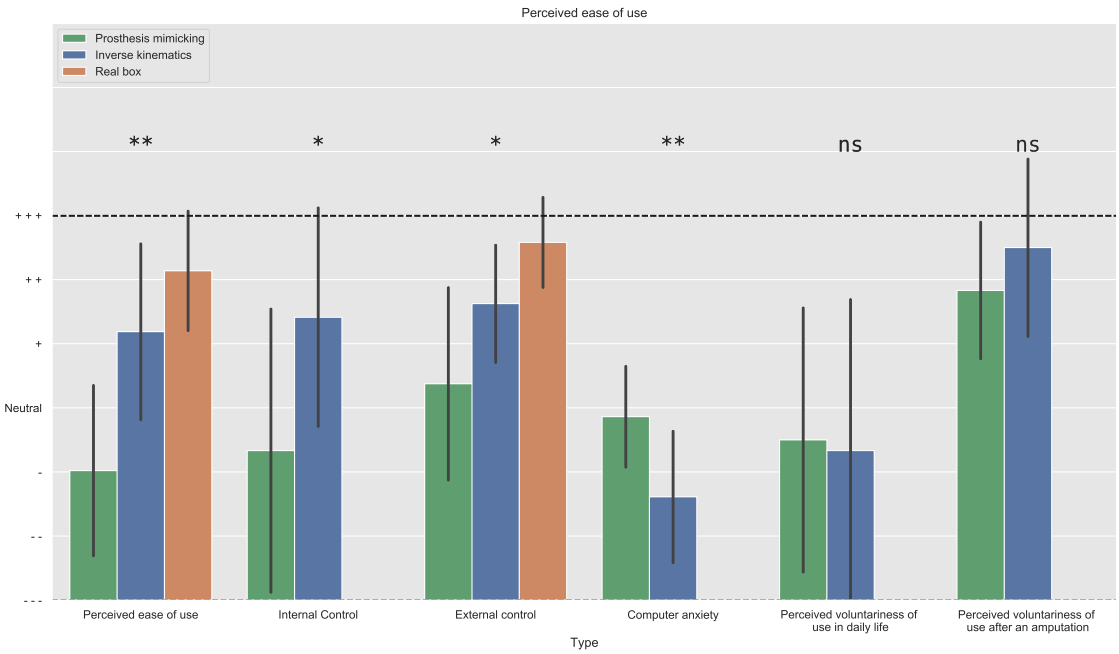

FIGURE 4.4: Responses of participants to different anchors of perceived ease of use. The real box bars are shown only for illustration as not all the anchors were evaluated. The significance levels are shown only for the comparison between inverse kinematics and prosthesis mimicking.

- perceived ease of use and all but one of its anchors (PVU in both cases) varies significantly between the two groups, being our inverse kinematics robot more easy to be used.
- the significant difference includes surprisingly computer anxiety, which does not relate with control excplicitly as only accounts for the feelings of the participant towards the robot.

4.2.4 Hypothesis 4 - Visual Analogue Scale for stress

The results for the first five VAS measurements are shown in Figure 4.5. The statistical test we used is a two-sided t-test. From the figure, it is evident that only measurement 1 shows a significant difference between classes. Measurement 1 is the first measurement of stress after immersion on the virtual reality. Therefore, PM participants express a very high degree of stress on the first trial, and it is subsequently reduced as they gain practice.

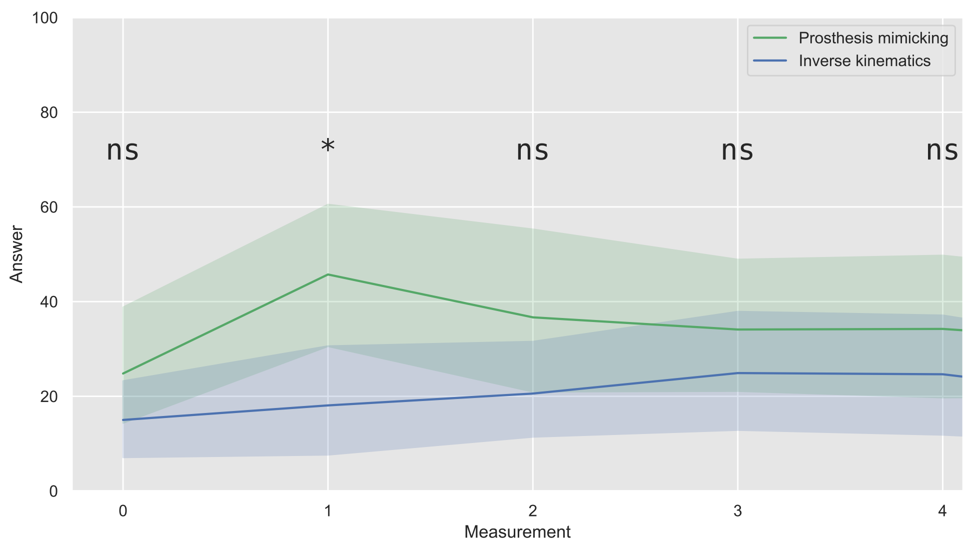

FIGURE 4.5: Answer to the question: 'Indicate on this slide how stressed you feel right now'. Shaded is the 95% confidence interval for the mean.

Chapter 5

Discussion

In the present chapter, I would like to discuss our experience with ArmSym, and point out potential directions of future research. On Section 5.1 I discuss the results of the pilot experiment, critically discussing our hypotheses. On Section 5.2 I talk about the next steps after the pilot study, highlighting some of my personal ideas with the system.

5.1 Discussion over the pilot experiment

It has been shown that it is possible to run a scientific experiment using ArmSym, and thereby test psychological phenomena using in-game and out-game questionnaires. In the next subsections, I explore the hypothesis, and discuss the results.

5.1.1 Performance

> ***Hypothesis 1****: The timed test in the ArmSym environment is satisfactory in the sense that:*
>
> a) *The users can perform the test in 10 or 20 trials with their assigned control mode without many glitches and in-game inconsistencies.*
>
> b) *The participants display a learning curve, and it relates to the learning curve in the real world test.*
>
> c) *The results of timed tasks (meaning the rate of blocks the users transfer) in IK participants are comparable with their results of timed tasks with a real box, on rates similar to the one proposed by Kontson.*
>
> d) *The result of timed tasks in PM participants approach the rates from the studies of Miller and Lambrecht.*

We were able to gather scientific data from all the subjects, both within the game and in the real world. Nevertheless, we have room for improvement. During our run of the experiment, we found only two non-trivial technical problems:

- The calibration session often produced unrealistically long or short robotic limbs. For almost all participants, the length of the real arm was measured with a flexometer and compared with the measurement at the calibration scene. If this two numbers were considerably different, or if the robot in the practice trial seemed unrealistically big or small, the calibration session was rerun. Only when this happened, the very first VAS measurement was retaken. We believe that the potential reason for this was occlusion between the trackers and the camera, as participants did not usually have a sense of where the camera was. Although the experiment was run successfully, it is strictly necessary that the next versions of the system update the calibration session.

- The times when a block crossed the partition were saved and appended on a list. Whenever one block accidentally fell on the partition and back to the original compartment, it was removed from the final score, but unfortunately not from the list of times for crossing the border. Therefore, the data saved for some trials has a larger number of crossing barrier times than its total trial score. This was only a problem when computing the time for the sixteenth block in the inverse kinematics. Therefore, on all the present accounts for 'times of the sixteenth block' within VR, we have removed those trials in which the score did not match the length of the appended crossing barrier times.

We deem hypothesis 1A to be true. Despite the problems with the calibration, we were able to run the experiment, and we learned how to improve the system.

As seen in Figure 4.1, the green learning curve - for prosthetic mimicking - has a very high learning rate. On the first trials, participants seldom do better than any of the three other studies, but as trials go they overpass pre-TMR control rates in Miller et al., 2008, and synchronous control as in Lambrecht, Pulliam, and Kirsch, 2011. The best participants surpass the average post-TMR results from Miller et al., 2008. The best prosthesis mimicking score was achieved by participant S16: 27 blocks, roughly 4.44 seconds per block. Therefore, we believe hypothesis 1D is true. However, it is not clear whether or not there is a plateau; likely there is not, it seems as if with more trials the average times would improve. We hypothesize that with more trials the rates would have approached those that Miller & colleagues found with post-TMR subjects.

The blue learning curve - for inverse kinematics - has a mild learning rate similar to the one in the real box, but does plateau on ca. trial 10. The best scores were made by S23, who peaked 66 blocks on their best trial, or about 0,9 seconds per block. Except for this participant, the inverse kinematics scores are not as close as expected to the real world test. The real world test starts with rates close to the median ones of Kontson et al., 2017, and then approaches the mean rates of the study from Miller et al., 2008.

Clearly the participants in the IK group were much closer in terms of performance to the real box test, but unfortunately they do not overlap. Our hypothetical explanation is the following: it is fairly easy for people to pick up a cube in real life without thinking too much. Cutaneous touch and sensory information allows for the users to execute an action without much visual feedback. This might make picking a cube in real life much faster than a cube in VR, even when the robot is moving like the real arm. Two other factors may also account for this difference: the weight of the controller, which prevents high speeds in the transit of the cube, and the fact that the VR box was filled with 100 cubes instead of 150 for game performance reasons. Based on this information and further data from Figure 4.2, we believe that hypothesis 1C is rejected. If it were true, there would be a clear correlation between the best time in VR and the best time in the real box. This correlation was not shown (PearsonR=0.1), and therefore we can claim that this hypothesis is not true. The only exception for this hypothesis is the sole participant who was able to go under 1 second per block, i.e., S23. This participant was also the fastest in the real box and blocks, and their VR rates is close to the median of the participants in the real box and blocks study by Kontson & colleagues.

Nevertheless, from Figure 4.1 it is evident that participants have a learning curve. In Tables 4.1 and 4.2 I explore further these learning curves. As can be seen from the table, three PM and four IK subjects display a strong significant correlation. 75% of all the IK participants have correlation trends of more than 0.35. In prosthesis mimicking, only 42% display this trend. The rejection of hypothesis 1B is unclear given the data. What is clear from the data is that *there is* a learning curve, and it is much more pronounced in the PM group.

5.1.2 Perception of embodiment

> ***Hypothesis 2****: In the absence of realistic cutaneous touch of the blocks and afferent information within VR, controlling a prosthesis nevertheless creates a perception of embodiment that:*
>
> a) *Appears in both levels of control, for which all participants tend to answer the question of perceived embodiment in a positive way of the Likert scale regardless of their group.*
>
> b) *Has different degrees of intensity correlated with control, for which the IK participants would have a significantly higher effect than the PM participants.*
>
> c) *The control questions 1 & 2 are consistently rejected by both groups.*
>
> d) *The control questions 0 discriminates the two control groups significantly, such that IK participants answer on the possitive side of the linkert scale and PM on the negative side.*

From the results shown in Figure 4.3, it is clear that both of the groups consistently answered negatively to control questions 1 & 2, and therefore hypothesis 2C is accepted. Control question 0 evidently discriminates significantly the two control groups, for which hypothesis 2D is accepted. Nevertheless, the perception of embodiment does not appear consistently in both levels of control, for which hypothesis 2A is rejected. Since the inverse kinematics group has answered to this question in a more positive way than the prosthesis mimicking group, hypothesis 2B is accepted.

These results about the user's perception of embodiment are really interesting. Indeed, as in the experiment by Rosén et al., 2009, we obtained a positive response to the question on the perception of embodiment in the absence of realistic cutaneous touch. On their study, Rosén & colleagues debate about the nature of such positive answer. Were the subjects triggered a rubber hand illusion? If not, was it then a more general sensation of embodiment, or just a biased answer or a matter of language? Our data cannot provide an answer for these questions, but also it does not reject the belief that control is influencing a general perception of embodiment. Out of the potential errors Rosén & colleagues report in their discussion (and accounting for their positive response), we can rule one out: the uncontrolled sEMG noise. They claim that, as there is no control over the myoelectric condition, it cannot be affirmed that there was a match between intentions and feedback, and that this could be a potential source of error. Our results dismiss this possibility because we are sure of the match between intentions and feedback. Indeed, one of the advantages of ArmSym is that it allows us to introduce the noise in a controlled way.

Our new hypothesis is that the feeling of embodiment is indeed influenced by the degree of control, i.e., the agency component as in Longo et al., 2008. But the judgment of the participants might have been biased by another component: location. At all times during the IK trials, the subjects had an efferent copy that coincided with their visual feedback. A good follow-up experiment would analyze what is the actual effect of this efferent copy in the perception of embodiment. Does it account for the total of it, or partially together with agency?

Two further comments should be made over the questionnaire in perception of embodiment. First, De Vignemont, 2011, proposes a debate over the use of a Linkert scale, as the results are difficult to interpet. Indeed, does the distance to the 'Neutral' axis reflect the vividness of the feeling of embodiment, or the confidence on the user judgment? (De Vignemont, 2011). Another way of examining the concept of embodiment may be by introducing behavioral tests. De Vignemont proposes some affective measurements of embodiment:

> *"(...) if E is protected from hazardous situations, and one reacts to threats to or injuries of E in the same way as one reacts when a part of one's body is threatened or hurt, then E is embodied".* De Vignemont, 2011

Second, in the questionnaire we make use of the word *arm* instead of the word *hand*. We found out that this is not as trivial as initially we had thought of: one participant mentioned he felt very comfortable with the shoulder-to-wrist part of the robot, but that he felt a misrepresentation in the hand, and that influenced him when answering the embodiment question. We formulate the following question: Would it be more efficient to ask questions about specific parts of the upper limb regarding the perception of embodiment?

5.1.3 Perceived ease of use

> ***Hypothesis 3****: The degree of control heavily influences the perceived ease of use of the robotic device, such that there is a significant difference in the measurements for PEU and all of its anchors between the two groups, and being the inverse kinematics robot more easy to use.*

As shown in Figure 4.4, this hypothesis is accepted for all the items except for perceived voluntariness of use. From the latter we would conclude that no matter how hard the control over a prosthesis would be, in case of an amputation the users would feel the need to wear a prosthesis. According to the technology acceptance model developed by Venkatesh, 2000, this alone is not a reason to guarantee the acceptance of the technology. An interesting follow-up experiment would be to test if this perceived voluntariness of use can be affected by extreme gaps in control, i.e., if participants are presented with tasks that have a low probability of completion. Think of the claw arcade game, also known as the teddy picker. People tend to be jaded after some interaction time, and perceived voluntariness of use would theoretically decrease.

Perhaps the most interesting result regarding this technology acceptance model is the one of computer anxiety, which showed a significant difference between groups. Paraphrasing the original author, robot anxiety can be defined as the apprehension or even fear (Venkatesh, 2000) that users have over using a robot prosthesis. It is interesting that these feelings are influenced by control.

Lastly, it has to be said that the PEU questionnaire is subject to error due to the fact that we adapted it from a domain that was fundamentally different: computer software for job-related applications. A rigorous psychological experiment would need to formulate a new questionnaire tailored to our application. This, however, is out of the scope of the present work.

5.1.4 Visual Analogue Scale for stress

***Hypothesis 4**: Participants from the inverse kinematics group report significantly less stress than the participants from the prosthesis mimicking group in all the measurements except for the first one, after calibration.*

As shown in Figure 4.5, this hypothesis is rejected, as only the second measurement (the first after starting) displays a significant variation in the level of stress according to the VAS. This is indeed valuable information: high stress levels when learning a task seem to be reduced in correlation with the learning itself. Further analysis would require the data from the pulse oximetry.

5.2 What comes next for ArmSym?

After the validation experiment, two different kinds of work interest us regarding ArmSym. Consequent to our initial formulation, we want to study both upper limb prostheses and BMI-controlled ARMs.

5.2.1 On the domain of upper limb prostheses

Two interesting research questions were formulated from our pilot experiment with ArmSym:

- Regarding perception of embodiment: ArmSym would be an interesting tool for testing the influence of location and agency towards the feeling of embodiment and perhaps ownership. An interesting experiment would be to maintain high levels of control as in the inverse kinematics group, but switch the visual feedback such that it does not match the efferent copy. We could also test how much controlled noise affects the perceived embodiment, or how much embodiment itself influences acceptance of robot assistants.
- Regarding the technology acceptance model discussed previously: it is interesting to know how much computer anxiety, perceived ease of use and perceive voluntariness of use change in correlation to differnet control levels of the prosthesis. Are they affected with certain degrees of noise? Would they change if the robot looked like a human arm?

5.2.2 On the domain of BMI-controlled ARMs

As shown in the Introduction of the thesis, one of the first motivations of ArmSym was to provide an environment in which we could test new control paradigms in BMI-Controlled ARMs, particularly information-theoretically efficient approaches inspired on the work of Omar et al., 2010. By using the infrastructure developed, including the algorithms for the inverse kinematics and the marker stream, we can formulate new experiments.

My personal vision over the topic is that shared control should exploit the developments in robot learning that have been happening in the last few years (Paraschos et al., 2018). Indeed, a shared control approach would require the robots to execute actions in a nearly-autonomous way. By joining robot learning techniques and ArmSym we could test whether these control methods are efficient, using a BMI or another low-thoughtput interface. We could also test the studied psychological metrics, which to our knowledge have never been researched in this domain.

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