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ESCUELA TÉCNICA SUPERIOR
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ESCUELA TÉCNICA SUPERIOR DE INGENIEROS DE TELECOMUNICACIÓN
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MÁSTER UNIVERSITARIO EN INGENIERÍA BIOMÉDICA

TRABAJO FIN DE MÁSTER

DEVELOPMENT OF A VIRTUAL REALITY ENVIRONMENT USING LEAP MOTION FOR DIAGNOSTICS OF HAND MOTOR DISORDERS OF STROKE PATIENTS.

LUCÍA SALLÉ MORENO

2020

MÁSTER UNIVERSITARIO EN INGENIERÍA BIOMÉDICA

Trabajo fin de máster

Título: Development of a virtual reality environment using Leap Motion for diagnostics of hand motor disorders of stroke patients.

Autor: Dña. Lucía Sallé Moreno

Tutor: D. Álvaro Gutiérrez Martín

Cotutor: Dña. María Alonso de Leciñana

Departamento: Robótica y control

Miembros del Tribunal

Presidente: D. ……………

Vocal: D. …………..

Secretario: D. …………..

Suplente: D. ……………..

Los miembros del tribunal arriba nombrados acuerdan otorgar la calificación de: ………

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Resumen

Este Trabajo de Fin de Máster se marcó como objetivo general desarrollar una herramienta de diagnóstico basada en mediciones objetivas para pacientes de ictus, a través de la creación de un entorno de realidad virtual basada en el uso del controlador Leap Motion. Para lograr el objetivo global, se establecieron una serie de pasos e hitos que se cumplieron consecutivamente durante la duración de este proyecto.

Se realizó una investigación bibliográfica con la comprensión necesaria del ictus en términos clínicos y del paciente. Este paso fue crucial para establecer los puntos clave que deberían incorporarse en el entorno desarrollado: la forma en que los neurólogos diagnostican la pérdida motora de la mano, las características más importantes que deben evaluarse, las carencias y limitaciones de los métodos de diagnóstico actuales, así como las necesidades de los pacientes con accidentes cerebrovasculares. Con estos antecedentes clínicos establecidos, una investigación exhaustiva del estado del arte permitió comprender cómo se está utilizando la realidad virtual hoy en día, sus limitaciones y su potencial. Estudiando sus aplicaciones en el entorno clínico, especialmente en el campo de la neurorehabilitación, pudimos establecer la mejor manera de abordar nuestro propósito específico.

A lo largo del desarrollo del TFM, se alcanzaron los siguientes cuatro hitos: definición de los ejercicios, desarrollo de un sistema de apoyo, implementación del entorno de RV y recogida de los datos necesarios. Para ello, se eligió el controlador de Leap Motion porque permite un seguimiento constante de las manos sin necesidad de electrodos o guantes, para que las manos puedan interactuar con un entorno de RV de forma natural. La plataforma utilizada para implementarlo fue Unity.

Después de elegir la tecnología apropiada, los ejercicios se definieron en colaboración con los neurólogos del Hospital Universitario La Paz. Los ejercicios se dividieron en dos módulos, uno en el que el paciente debe replicar cuatro movimientos diferentes con ambas manos, sin interacción con el entorno, y un segundo que consiste en un simple juego en el que los pacientes agarran cubos virtuales y los arrastran hasta un punto específico, con el fin de evaluar el rendimiento de una manera orientada a la tarea y atractiva.

La condición física y las limitaciones de los pacientes con ictus tenían que ser consideradas al concebir la forma en que los pacientes utilizarían el entorno. Por lo tanto, se diseñó un sistema de apoyo que incorporaba los requisitos técnicos de Leap Motion para garantizar un uso óptimo.

Una vez que todo fue definido, los ejercicios fueron implementados en Unity. El entorno desarrollado permite rastrear y registrar constantemente las variables más importantes de la mano del paciente, tales como la posición y la velocidad del centro de la mano y los dedos.

Con Matlab se creó una herramienta de análisis para reconstruir y analizar la información registrada, y extraer una serie de tablas y gráficos con las variables más importantes, incluyendo la evolución de la velocidad o el movimiento del centro de la mano y los dedos en el plano y a lo largo de todas las direcciones. Finalmente, se realizó el análisis de estos resultados para un único sujeto, y así probar la coherencia del resultado, así como para ejemplificar cómo los gráficos deben ser vistos en un análisis de caso real.

Summary

This MSc Thesis had the overall aim of developing a diagnostic tool based on objective measurements for stroke patients through a virtual reality environment that relied on the use of the Leap Motion controller. To achieve the global goal, a series of steps and milestones were set and met consecutively during the duration of this project.

A bibliographical research was done with the needed understanding of stroke in clinical and patient's terms. This step was crucial to settle the key points that should be incorporated in the developed environment: neurologists' way of diagnosing motor loss of the hand, the most important features to be evaluated, what current diagnosis methods are lacking and stroke patients' constraints and needs. With this stablished clinical background, a thorough state of the art investigation allowed to understand how virtual reality is being used nowadays, its limitations and potential. Studying its applications in the clinical environment, especially in the neurorehabilitation field, we could settle the best way to approach our specific purpose.

In the MSc Thesis, the following four milestones were reached: defining the exercises, developing a support system, implementing the VR environment and collecting the required data. For that purpose, Leap Motion's controller was chosen because it allows a constant tracking of the hands without need for electrodes or gloves, so the hands can interact with a VR environment in a lifelike way. The platform used to implement it was Unity.

After choosing the appropriate technology, the exercises were defined in collaboration with La Paz University Hospital neurologists. The exercises were divided into two modules, one in which the patient must replicate four different movements with both hands, with no interaction with the environment, and a second one consisting on a simple game where patients grab virtual cubes and drag them to a specific point, with the purpose of evaluating performance in a task-oriented and engaging way.

The physical condition and constraints of stroke patients had to be considered while conceiving the way in which the patients would use the environment. Therefore, a support system was designed, incorporating Leap Motion's technical requirements to guarantee an optimal use.

Once everything was defined, the exercises were implemented in Unity. The developed environment allows to constantly track and record the most important variables about the patient's hand, such as position and speed of the hand center and fingers.

With Matlab, an analysis tool was created to reconstruct and analyze the recorded information, and to extract a series of tables and graphs with the most important variables, including speed evolution or movement of the hand center and fingers on the plane and along every direction. Finally, the analysis of these outputs for one subject was done to test the coherence of the outcome, as well as to exemplify how the graphs should be looked at in a real case analysis.

Keywords

Stroke, virtual reality, diagnosis, motor function

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1 Introduction and objectives

1.1 Introduction

Stroke is the second cause of mortality worldwide, the first cause of disability and second for dementia [1]. It implies a huge charge for the healthcare system and an economic and social burden. It is also the first cause for death in women, and the second overall cause of death in Spain [2]. Although incidence is decreasing, life expectancy increase implies an aged population and a progressively increasing number of cases of stroke.

Up to 85% of patients suffer from hemiparesis as a symptom after acute stroke, which reduces mobility of the hand or the whole arm in the affected side of the body. A large proportion of these patients do not recover from these symptoms six months after the episode, which deeply affects their ability to perform daily activities and get full independence [3].

In order to try to alleviate patient's symptoms, an effective rehabilitation is needed, especially during early stages after the stroke occurred, while neuroplasticity mechanisms are still working and can guarantee good results in the recovery process. One of the key aspects to obtain so is a treatment oriented specifically towards patient's deficit. In particular, a precise evaluation of the motor function of the hand can help to predict patient's prognosis and future response to rehabilitation.

For both rehabilitation tasks and precise diagnosis, current evaluative practices are not discriminative enough and rely on subjective and rough observations done by the practitioner. This is why new techniques related to virtual reality applied for neurorehabilitation have started to be explored. These new tools create a controlled environment that replicates reality-like situations so that the patient can perform certain tasks safely while being monitored. The data collected can provide useful information that may not be obvious at first sight. Furthermore, they reduce the need for specialized practitioners and improve patient's independence and improve motivation thanks to gamification and tailoring of tasks.

In this context, the department of Robotics and Control at UPM [1] decided to partner with the neurology service at University Hospital La Paz. The objective is to design and create an evaluation tool aimed at quantifying stroke patients' hand motor loss while at acute phase. Therefore, more detailed information is obtained on their state and prognosis, and an optimal rehabilitation therapy for each case can be planned.

The technical device to be used within the project was the Leap Motion Controller [4], a small, low-cost, optical hand-tracking module that allows the interaction of one's hands with the interface in a very life-like way. Cameras and infrared light are used so that no electrodes are needed and hands can move freely while being continuously tracked with submillimeter accuracy, giving detailed information on each element of the hand's position and speed.

The conceived applications for the Leap Motion are plenty, but it has been used mainly for entertainment or even training purposes. Some clinical studies have been done aimed at comparing the results obtained with conventional therapy to those of rehabilitation using the device. Although evidence is not yet strong enough due to the lack of information, initial conclusions indicate that rehabilitation that incorporates virtual reality elements provides with slightly better and faster results.

[1] http://robolabo.etsit.upm.es/

However, all studies done in the field are focused on rehabilitation instead of quantitative diagnosis, which is also a key step in patient's path to recovery.

The exercises designed in this MSc Thesis will have to evaluate main hand functions that have an impact on patient's daily life, such as pinching of each finger against the thumb and wrist and finger extension. These exercises can emulate those performed on the ARAT [5] and Fugl-Meyer [6] scale. These two scales are the evaluation tool used by doctors to asses proximal and distal functional state after stroke. They define a series of tasks to be done by the patient and it is the practitioner who assesses a score depending on patient's performance.

Although sometimes not much more than an overall evaluation is needed to know what the patient's health state is, these measures are subjective and variable between operators. Furthermore, there are times in which the patient states a certain difficulty or pain that does not correspond to a visible affectation. This is why an environment designed for this specific purpose may have an impact on diagnosis procedures, increasing accuracy and sensibility to events, besides being useful for designing tailored and more engaging rehabilitation tasks.

1.2 Objectives

This MSc thesis aims to develop a diagnostic tool based on objective measurements for stroke patients. This tool is based on a virtual reality environment that allows a constant monitoring of the hand movements by a Leap Motion device.

The ultimate goal is to achieve a diagnostic method capable of discerning complex cases in which the observations at first sight of the clinicians are not sufficient. In addition, it will provide extracted data to relate this diagnosis to the clinical situation of the patient and his or her prognosis.

To achieve so, this main goal has been subdivided into smaller goals that can be achieved consecutively and that represent a challenge to be faced and solved by itself. These objectives are the following:

1. **To understand the gaps not covered by current diagnosis methods in the assessment of hand motor loss after stroke**: An immersion at the neurology service at University Hospital La Paz will allow the understanding of patient's situation at arrival at the stroke unit, their needs and their caregiver's needs. A special focus will be set on understanding current diagnosis methods for hand motor loss, and the points where physicians perceive they are not precise enough and the needs they do not cover.

2. **To define a series of exercises in collaboration with the neurologists and to replicate them in a virtual reality environment.** After the observation phase and with the input received from neurologist's and rehabilitators, a set of exercises will be defined in order to replicate them in a virtual reality environment.
   These exercises should be executable with Leap Motion, easily understood and done by the patient, provide useful information that is not perceived at sight by practitioners and provide some extra features that make the process more attractive and engaging through gamification.

A thorough state of the art research must be done to understand current uses of virtual reality in neurorehabilitation and clinical research.

3. **To define the physical conditions for the appropriate performing of the exercises.** The exercises must be performed in a specific set of conditions in order to guarantee reproducibility and precision. To achieve this, a user's guide will have to be defined. These instructions and restrictions must be easily achieved and require no effort from neither the practitioner nor the patient, but guarantee that the results obtained are reliable.

4. **To define a way to collect detailed information on the patient's hand while performing the exercises.** One of the most relevant aspects will be to collect precise information on the patient's hand, such as fingers' position and speed, hands' position and speed and time required to perform tasks. These variables must be continuously tracked at a defined rate and provide information not appreciable by practitioners at sight.

5. **To develop and to implement a virtual reality environment.** With the information from the previous phases, the defined exercises will be captured in a virtual reality environment created with Unity. These exercises will be created as a set of games based on the Leap Motion technology.

6. **Data collection on control subjects and stroke patients.** Once the environment is operative, an initial trial on both control subjects and stroke patients will serve as a technical validation of the technology. This will allow a first approach for evaluating the usability and usefulness of the developed tool, fix bugs and incorporate feedback from users, either practitioners or patients.

7. **To analyze extracted data.** With the collected data, key parameters will be analyzed and movements will be reconstructed in order to study coherence and precision of the tracking and obtain the technical validation required prior a clinical essay.

1.3 Thesis organization

This MSc thesis has been structured as shown in **Figure 1**:

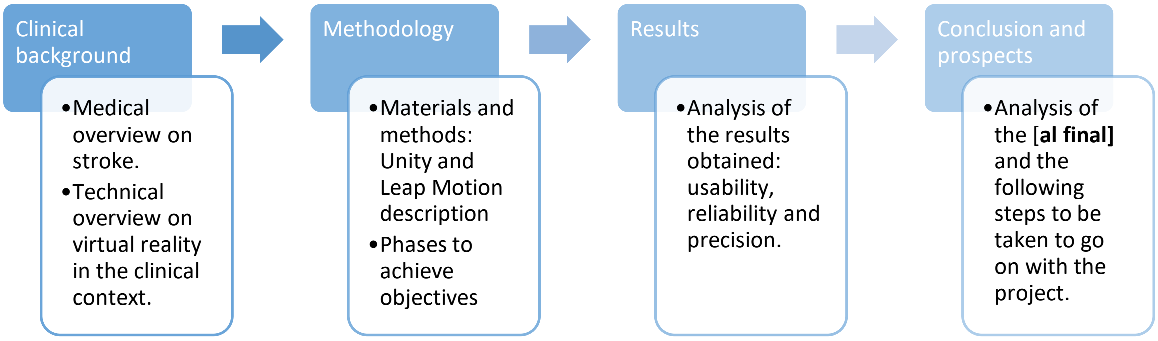


Figure 1. Outline of this MSc Thesis

- **Chapter 2: Clinical background.** In this chapter we find an overview of the clinical aspects that concern this Thesis. On the medical side, we have a brief synopsis of the most important points regarding stroke: symptoms, diagnosis process and types of strokes. A special focus is set on the upper limb motor function loss, studying the causes, implications and scales currently used for its assessment, which are the ones that are going to serve as a model to be replicated on the virtual reality environment. There is also a study on the prognosis and rehabilitation of stroke patients before getting into the technological background, where we have an overview of virtual reality for clinical uses, specially neurorehabilitation, in order to understand the direction current investigations in the field have.

- **Chapter 3: Methodology.** This chapter includes a description of the materials and methods used – Unity and Leap Motion- and the different phases that have been developed to achieve each of the objectives.

- **Chapter 4: Results.** It analyzes the data collection and its compliance to the expected results. Analysis of the usability of the environment, the precision of the measures and the overall reliability of the module as a diagnostic tool for clinicians. This chapter could not be completely tested with stroke patients due to the CoVid-19 [7] crisis that prohibited the access to hospitals and patients.

- **Chapter 5: Conclusions and prospects.** This chapter concludes the manuscripts and raises future work implementations.

In the annexes, two guidelines have been developed to ease and facilitate further investigation and implantation of the module:

A. **Clinical user guide:** a set of instructions to be followed by the practitioner who might use the module in the clinical environment.

B. **Developer's handbook:** a detailed description of every part of the code and Unity environment so that anyone can continue with this research where it has been left off.

2 Clinical background

Stroke is a cerebrovascular disease occurring after blockage or breaking of a brain blood vessel. It is a major health problem in countries with high lifespan, being the second cause of mortality worldwide, the first cause of disability and second for dementia [1], affecting a total amount of 15 million people each year [8], which implies great costs in economic, social and healthcare terms [9]. Symptoms, diagnosis methods and confirmation tests are explained here below.

One of the main consequences of stroke is upper limb motor function loss, happening in most patients suffering from it. Furthermore, it is one of the hardest capabilities to recover [10]. Apart from the primary lesion producing the loss, there are secondary effects that avoid patients from recovering or worsen the condition, such is the case of learned nonuse, learned bad use and forgetting, all of which will be detailed hereafter.

Measurement of recovery of normal function after stroke is important due to its relationship with patient's prognosis prediction and patient's recovery of critical functions, such as pinching. A precise characterization of the patient's status can help defining a proper treatment for each specific case.

Current techniques aim to provide a measurable scale for motor function assessment, reducing variability related to different operators and different tests. Some of the scales used in clinical practice, such as the NIH scale [11], Fugl-Meyer scale [12] or the ARAT test [5], are described in the following sections.

At arrival at the hospital, prognosis prediction is very important due to its relationship to rehabilitation, where certain conditions of the patient will imply different approaches to rehabilitation, depending on restorable functions. In the case of upper limb motor function recovery, rehabilitation relies on task-oriented exercises.

Ongoing efforts in the neurorehabilitation field are going towards introducing new technologies to solve the observed problems. Some of these research areas aim to provide practitioners with a standardized protocol that allows a quantifiable measuring procedure that does not depend on the technician's observations. Several of these techniques are also discussed in this chapter. A study of the current status of virtual reality and its applications on clinical environment is done in order to set the ground for the development of a module that tackles the identified problems.

2.1 Stroke

Stroke is a cerebrovascular disease occurring after blockage or breaking of a brain blood vessel, producing a lack of irrigation in the affected brain area that can end in neurons death due to the absence of oxygen and nutrients. [2] This situation, known as ischemia, can result in infarction, where dead cells are replaced by a fluid-filled cavity [13].

Some of the risk factors affecting the developing of this disease are old age (from 55 years old, the risk of suffering from stroke doubles each year), heritage, cardiovascular disorders such as hypertension or atherosclerosis, and other disorders such as diabetes [14].

Symptoms of stroke are sudden numbness or weakness in the face or extremities, especially of one side of the body; confusion and problems with language and understanding; troubles seeing; problems with coordination and walking; sudden severe headache [15].

Stroke is a major health problem in industrialized countries with high lifespan, being the second cause of mortality worldwide and the first in women, the first cause of disability and second for dementia. In Spain, although death rate produced by ictus has been reduced during the last decade, it is the second cause for death in men and first in women over 70 years old [2].

These statistics translate into 15 million people worldwide affected by stroke each year, 650.000 of those cases occurring in Europe. From those suffering from stroke, one third (5 million) die and another third are permanently disabled due to the lesion [8].

This implies a great socioeconomical burden, and this is why medical attention for this type of patients is crucial. It must be divided into four main areas: primary prevention of risk factors (diabetes, tobacco consumption…), urgent diagnosis and treatment at specific units within neurology services, secondary prevention to avoid recurrences and rehabilitation of patients who suffer from sequels [2].

Risk factors can be either unavoidable or preventable. For the first case, we find factors like old age, male sex, race, geography, season and weather and genetic factors. On the other hand, modifiable risk factors are arterial hypertension, diabetes mellitus, tobacco consumption, alcohol and drug consumption, dyslipidemia, heart pathologies such as auricular fibrillation, transient ischemic attacks and asymptomatic carotid atherosclerosis [2]. In particular, high blood pressure is linked to more than 12.7 million strokes worldwide [8].

2.1.1 Symptoms

Cerebral stroke is a general term that requires a greater precision by addressing etiopathogenesis, localization, ischemic or hemorrhagic origin, severity, etc. Stroke does not have a unique alarm sign nor a dominant cause, which is why a series of general symptoms have been defined in order to identify stroke [2]:

1. Weakness and numbness of one side of the body.
2. Vision difficulty in one or both eyes.
3. Difficulty to understand or produce language.
4. Vertigo or instability, associated to one of the previous symptoms.

Depending on the size and localization of the injury, the severity of the affectation and its permanence over time vary. There is a significant correlation between motor performance, functional outcome and brain lesion locations [16], which means that a precise evaluation of motor function can be used as a predictor of patient’s prognosis and recovery expectations. If this analysis is linked to their diagnosis and clinical status, an even more precise prediction could be obtained.

2.1.2 Diagnosis

EARLY EVALUATION

Evaluation measures for early recognition of stroke are key in order to guarantee the "Survival Chain", which refers to the links critical to improving the chances of survival and recovery for heart attack and stroke. These links include all the phases from early recognition, early CPR, defibrillation, life support and post-cardiac arrest care [17].

The most used evaluation scales are:

1. **Cincinnati Prehospital Stroke Scale**: fast prehospital evaluation of stroke aiming to get a rapid diagnosis to plan a proper intervention as fast as possible. The signs analyzed are facial drop, arm drift and slurring of speech. [18]
2. **Face-Arm-Speech Time test (FAST):** early evaluation of stroke symptoms based on the named features.
3. **Los Angeles Prehospital Stroke Screen:** predictive method used to identify potential stroke victims based on their age, past medical history of seizures, current blood sugar, duration of symptoms, current hospitalization status and motor asymmetry.

DIAGNOSIS CONFIRMATION

The approximation to diagnosis done by doctors at patient's arrival to the hospital is based on the medical record and a physical exploration performed to localize and characterize the lesion.

The neurodiagnostic tests performed on the patient are used to ease the diagnosis procedure. They can be both structural and functional. Structural tests show internal anatomy, whereas functional ones represent an extension of the neurological exploration, showing metabolic and electric functions of the body. Tissue and body liquid analysis are also required in some cases [19].

Structural tests are very relevant in lesion evaluation. The main modalities used for diagnosis and progression are:

- **CT scan:** first image modality used in stroke diagnosis confirmation due to its accuracy. It serves to distinguish between hemorrhagic and ischemic stroke, or even to identify a different underlying cause for the patient's symptoms. See **Figure 2**.

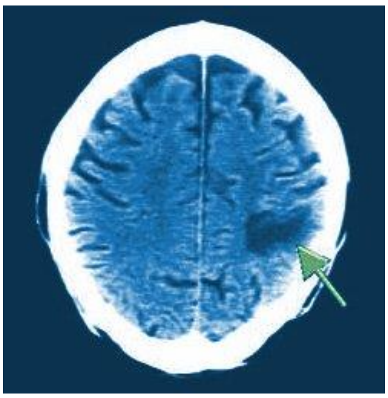


Figure 2. CT scan of a stroke. Source: The Internet Stroke Center.

- **Magnetic Resonance**: used when higher detail on the lesion structure and tissue affectation is needed. See **Figure 3.**

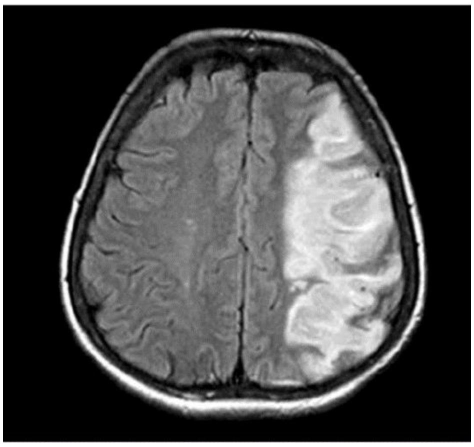


Figure 3. MRI of a stroke [8].

- **Angiography:** done in those cases where aneurism or thrombosis is suspected. Used to localize where the occlusion or rupture of the vase is, and to decide whether an embolization is necessary. See **Figure 4.**

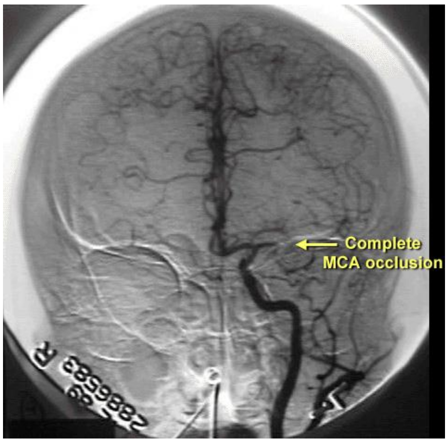


Figure 4. Angiography of a stroke [8].

Within **functional tests,** we find electroencephalography (EEG), nerve conduction study, evoked potentials, positron emission tomography (PET) and single positron emission computed tomography (SPECT) [19]. However, the most used in the clinical environment is EEG, which registers the neurophysiological activity of the brain through electrical signals on the surface of the skull [20]. This test allows the detection of abnormal activity produced by the lesion, and is performed on patients who present convulsions, encephalopathy or brain death [19].

2.1.3 Types of stroke

Strokes are separated into two main groups: ischemic (infarcts) and hemorrhagic [2].

Around 80% of all strokes have an ischemic origin [2]. They are produced due to a thrombosis or embolism.

Most frequent types of **ischemic stroke** regarding clinical manifestation, as depicted in **Figure 5**, are:

- **Lacunar stroke:** small lesion (3mm to 2 cm) named lacune, produced by the lack of oxygen in the region following a clot that produces an embolus in the small arteries of the brain [21]. In general, lacunar strokes have a better prognosis than strokes affecting bigger blood vessels. They account for 15-20% of all strokes [2].
- **Transient ischemic attacks:** characterized by short episodes (less than 24h) of focal neurological function loss [22]. They are a predictor for stroke and heart attack. They account for 15-20% of all strokes.
- **Atherothrombotic stroke:** this type of stroke is very frequent in patients with atherosclerosis with risk factors such as old age, hypertension and diabetes. 75% of them are preceded by transient ischemic attacks. They happen in a several hour period.
- **Cardioembolic stroke**: characterized by a very sudden deficit, low level of consciousness and coexistence of systemic embolism [2]. Extensive strokes (atherothrombotic and cardioembolic) account for 45-50% of all strokes [2].

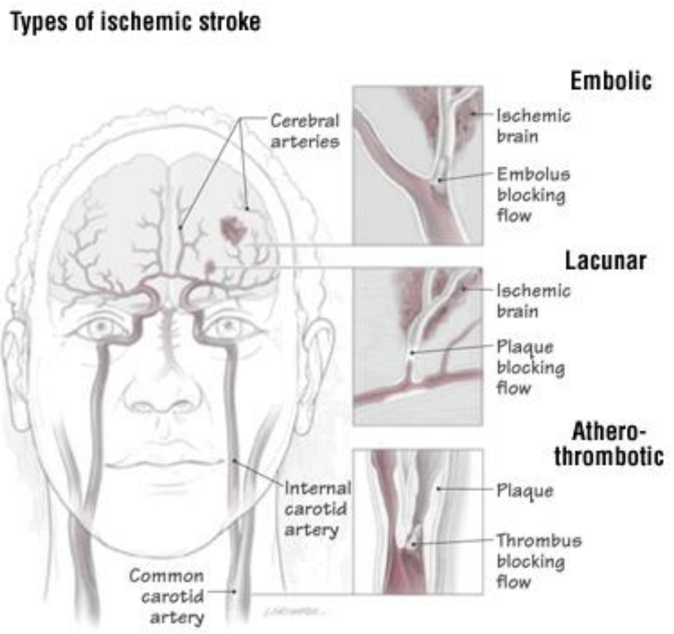


Figure 5. Types of ischemic stroke [21].

Hemorrhagic stroke is produced by the rupture of a cerebral vessel that produces a hemorrhage that can be cerebral (10% of all strokes) or subarachnoid (1-2% of all strokes) [22] (See **Figure 6**). Rupture can be produced by:

- Aneurism
- Arteriovenous malformation
- Transient ischemic attacks

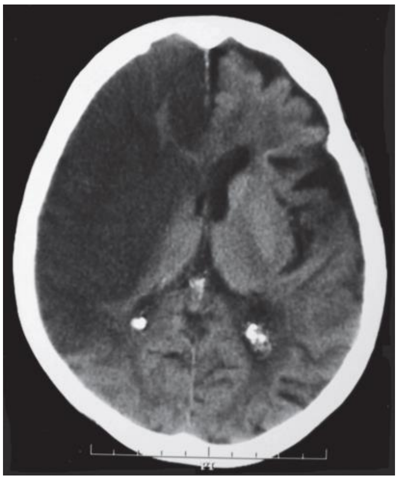


Figure 6. Hemorrhagic stroke [2].

2.2 Upper limb motor function loss

Motor function is a very complex component of the organism, involving several systems and plenty of different structures in order to produce movement, either voluntary or autonomous. Some concepts will not be thoroughly explained, since it is not necessary for the development of this project to know in detail the physiological mechanisms behind motor response. However, a brief summary serves to understand following decisions made along doctors and physicians. Most of the following information was provided by doctors at the Neurology unit in University Hospital La Paz.

Basic axis for motor regulation is the corticospinal system, in charge of associating primary motor areas with the anterior marrow stem. Other neural systems act over this axis in order to modulate all the motor functions: motor units, descending systems from the primary motor cortex and the brain stem, the base ganglia, the cerebellum and integration areas [2].

Motor control is a descending pathway going from the cerebral cortex in the parietal lobe, with a contralateral action while descending towards the body. Neurons descend through the pyramidal pathway and reach the spinal cord motor horn through the brain stem.

In the cervical region of the spinal cord, nerves are arranged in groups named myotomes, each of which innervates a specific body part and muscle group. The myotomes affecting hand movement are located at:

- C5-C6: innervates index and thumb fingers for pinch movement, plus wrist extension.
- C7: innervates middle finger.
- C8-T1: innervates ring and little fingers.

The corresponding nerves within these myotomes are:

- Median: in charge of pinching.
- Cubital: in charge of hand deviation towards cubital side and extension of ring a little finger.
- Radial: in charge wrist and finger extension.

With this in mind, a discrimination between peripheral or global lesions can be done, based on the motor functions affected. Central lesions will produce a general weakness, translated in the whole hand losing function, whereas peripherical lesions will only affect those muscles innervated by the affected nerves. Symptoms will be different depending on the level where the lesion appears.

Weakness or paralysis is the most prevalent impairment happening after stroke, due to the non-transmission from the motor cortex to the spinal cord. This translates in a retardation of the electrical impulse that generates muscle contraction, and so a delay in movement performance and force execution, which produces an inability to move the limb or to move it at the expected speed [23].

This symptom can be evaluated through MEG analysis, since patient's efforts to produce movement often generate an increased rate of MEG signal. This rate of force development in wrist extensor and handgrip strength are good predictors of upper limb function [23].

Another factor affecting hand movement is deep sensibility. Proprioceptive sensibility regulates movement precision, smoothness and control. An alteration of this function produces sensitive ataxia, which means that the patient loses movement precision only while their eyes are closed, (i.e, without controlling it through sight). However, ataxia can also appear in cerebellum affectations, but in this case, it is a general ataxia where precision in movement is lost regardless patient's eyes being open or closed. This difference is useful to determine the origin of the symptoms. Other effects of sensory loss across tactile or proprioceptive modalities are two-point discrimination, stereognosis (ability to recognize the shape of an object through tactile stimulus with no auditory or visual information) and graphesthesia (ability to recognize writing on the skin through the sense of touch).

Another motor disorder occurring after stroke is spasticity [23] , whose prevalence increases over time after the episode, since it is related to immobility and weakness occurring as a consequence of primary motor disorders. Spasticity consists in an increased muscle tone produced by hyperexcitability of the stretch reflex.

In order to understand motor function loss and plan therapeutic efforts, it is also important to keep in mind several aspects, such as impairment's evolution in time, that might change in nature while progressing; and that multiple causes may be producing the impairment [23].

Also, while considering patient's status and planning recovery, the three main functional consequences of impairments on upper limb must be taken into account:

1. **Learned nonuse**: due to initial numbness, weakness or sensory loss of the arm, patients learn not to use the affected limb. When they recover the normal function, they do not reincorporate the arm to normal function, due to this learned nonuse. Both weakness and proprioceptive alterations lead to immobility, which can later produce other affectations of the limb that worsen motor impairment, such as contractures that generate spasticity or bone mineral density alteration that increases the risk of developing osteoporosis in the hemiparetic limb.

Also, chronic loss of sensation implies other consequences, including an altered perception of stimuli and internal representation of a task, generating inability to control motor output, and neuronal hypersensitivity that generate central pain and accentuates learned nonuse effect.

2. **Learned bad use**: the three symptoms explained before (weakness, sensory loss and pain), added to stiffness and contractures resulting from immobility, produce compensatory strategies to generate movement. Some of said strategies are: "trunk flexion rather than elbow extension to reach for objects, forearm pronation and wrist flexion rather than neutral forearm position and wrist extension to orient the hand for grasping, and metacarpophalangeal (MCP) joint flexion rather than proximal interphalangeal (PIP) joint flexion to grasp objects". These compensatory techniques guarantee short-term success in achieving tasks, but overall accuracy and precision are actually reduced comparatively to proper functioning. This positive feedback reinforces compensation and generates learned bad use. However, normal function can be restored by preventing accessory movements. For instance, by fixing a patient's trunk to a chair, they force the normal function of elbow extension to achieve the task.
   Spasticity is considered one of the generators of learned bad use. At first, this secondary motor disorder is considered a good sign, since it means that the electrical transmission of motor impulses is happening. In fact, patients with spastic co-contraction have a higher score in the Fugl-Meyer scale and are considered to be further along up the recovery path. However, this co-contraction means the recruiting of inappropriate antagonist fibers and muscular groups, which oppose to the intended movement and end up generating involuntary movements and impairment in the active function. [23]
   "When spasticity is present, the cost of care is 4 times higher than when spasticity is absent; however, because spasticity is strongly associated with stroke severity, the independent impact of spasticity on costs is not known". [10]

3. **Forgetting:** motor skills recovery after stroke is not permanent and the restore of motor functions has been shown to be transient when rehabilitation is stopped. In order to guarantee permanency of the results achieved through therapy, three processes must occur independently:

   a. "Precise task-specific sensory-motor mappings occurring through trial-and-error adaptation during practice with appropriate error sensing". This means a reduction in movement bias and the correction to a proper movement, which is easily forgotten.
   b. Repetition of tasks. This generates a slow tuning into the right movement.
   c. Reinforcement through intrinsic or extrinsic rewards after a right movement is achieved.

It is important to consider, while planning rehabilitation, that adaptation of reach and grasp are heavily impaired and not easily recovered despite repetition. This is produced due to the interconnection of sensory-motor functions. In order to recover motor function, patients require sensory inputs such as "kinesthetic sense from muscle forces, tactile sensation from touch receptors and visual input about object contours."

2.3 Upper limb motor function assessment

Neurologists evaluate patient's motor function through the NIH scale [11] and a muscular balance evaluation. This provides with a rough understanding on the patient's situation and affectation of the limbs. The three main aspects to take into account are muscle tone, muscle force and muscle consistency, which are evaluated through examination of articulations mobility, symmetry and strength [19].

However, rehabilitators use more precise scales aimed at precisely defining the patient's loss of function. The most important scales used for this purpose are explained in the next subsections.

Currently, there is a lack of standardization in clinimetric evidence for upper limb motor assessment post-stroke. This happens because of several reasons: novel metrics are continuously created or adapted instead of performing clinical research on existing ones. Some methods like the Fugl-Meyer and ARAT require hardware that is not widely available. Validation requires very well-designed studies and large cohorts [24].

Prospective studies on different kinematic metrics for post-stroke assessment summarized the parameters most frequently used, their validity, quality and the evidence they provide in terms of clinical evaluation [24] are shown in **Table 1.**

Kinematic Metric	Clinimetric Property	Quality of Evidence	Summarized Evidence	Quantitative Evidence
No. of movement onsets	Validity (+)	Moderate	Sufficient	lrl: −0.54
No. of movement ends	Validity (+)	Moderate	Sufficient	lrl: −0.58
Task/movement time	Validity (+)	High	Sufficient	lrl: −0.60; −0.60; −0.53; −0.52
Path length ratio	Validity (+)	Moderate	Sufficient	lrl: −0.54; 0.85
No. of velocity peaks	Validity (+)	Moderate	Sufficient	lrl: −0.58
Shoulder flexion/extension angle	Validity (+)	Moderate	Sufficient	lrl: 0.50; 0.56; 0.59; 0.70
Trunk displacement	Validity (+)	Moderate	Sufficient	lrl: −0.76; −0.72; −0.68
Range of velocity	Validity (−)	Moderate	Insufficient	lrl; −0.4
Peak velocity	Reliability (+)	Moderate	Sufficient	ICC: 0.74; 0.74; 0.87; 0.87; 0.93; 0.93; 0.94; 0.95; 0.95

Table 1. Overview of the kinematic metrics and their clinimetric properties [21].

These parameters are assessed differently in the most-used scales, using different approaches and exercises, which are explained hereafter.

2.3.1 NIH Scale

The NIH Stroke Scale (NIHSS) International is a scale aiming to standardize clinical evaluation of patients having suffered from stroke. "The National Institutes of Health Stroke Scale (NIHSS) is a systematic assessment tool that provides a quantitative measure of stroke-related neurologic deficit. The NIHSS was originally designed as a research tool to measure baseline data on patients in acute stroke clinical trials. Now, the scale is also widely used as a clinical assessment tool to evaluate acuity of stroke patients, determine appropriate treatment, and predict patient outcome" [11].

By evaluating severity and level of affection of the patient, NIHSS can be used to predict patient's expected outcome. It is defined as a 15-item test that evaluates neurological function, from level of consciousness to the presence of symptoms like limb ataxia, parrhesia or dysarthria. It rates each question with 3 to 5 possible scores, going from 0 (normal state) to 4. The final score obtained after addition of each question gives a general overview on the patient's condition.

2.3.2 Action Research Arm Test (ARAT)

The ARAT was first defined by Lyle in 1981 as a modification of the Upper Extremity Functional Index (UEFI). "UEFI is is a patient report outcome measure used to assess functionality in the upper extremities in individuals with upper limb dysfunction of musculoskeletal origin" [25]. It consists of 20 or 15 questions rated from 0 to 4, with a higher score indicating a better motor function. These questions are related to daily functions that require upper limb use.

In contrast to UEFI, ARAT aims to provide with a more reliable measure of patient recovery of motor function after score. In this case, the test consists in 19 tests, divided into 4 subsets depending on the task, with a score going from 0 to 3. [5] Both hands are analyzed, studying the strongest firstly and the most affected one in the second place. The way to assess scores goes as detailed in **Table 2**:

Score	Description
3	"Task is performed normally. This requires the task to be completed in less than 5 seconds, appropriate body posture, normal hand movement components and normal arm movement component"
2	"Task is completed but either with great difficulty or takes abnormally long. Great difficulty is defined as (1) abnormal hand movement components [...], (2) abnormal arm movement components [...], or (3) abnormal body posture [...]. The amount of time used to distinguish a score of 2 versus 3 was not specified by Lyle [...]. Takes abnormally long is defined as 5 to 60 seconds."
1	"Given when the subject only partially completes the task within the 60 seconds allotted for examining each task"
0	"Given when the subject is unable to complete any part of the hand or arm movement components withing the 60 seconds allotted for examining each task"

Table 2. Description of scores on the ARAT scale.

The four analyzed subscales are Grasp (1-6), Grip (7-10), Pinch (11-16) and Gross Movement (17-19) (see **Figure 7**). The order in which the tasks are performed within each subscale is firstly the most difficult and secondly the easiest, in order to predict performance of patient in subsequent tasks [5].

Table A1. Action Research Arm Test Scoring Sheet

Test Number	Item	Score	
	Grasp subscale	Left	Right
1	Block, 10 cm³	0 1 2 3	0 1 2 3
2	Block, 2.5 cm³	0 1 2 3	0 1 2 3
3	Block, 5 cm³	0 1 2 3	0 1 2 3
4	Block, 7.5 cm³	0 1 2 3	0 1 2 3
5	Cricket ball	0 1 2 3	0 1 2 3
6	Sharpening stone	0 1 2 3	0 1 2 3
		Subtotal ____/18	____/18
	Grip subscale		
7	Pour water from one glass to another	0 1 2 3	0 1 2 3
8	Displace 2.25-cm alloy tube from one side of table to the other	0 1 2 3	0 1 2 3
9	Displace 1-cm alloy tube from one side of table to the other	0 1 2 3	0 1 2 3
10	Put washer over bolt	0 1 2 3	0 1 2 3
		Subtotal ____/12	____/12
	Pinch subscale		
11	Ball bearing, held between ring finger and thumb	0 1 2 3	0 1 2 3
12	Marble, held between index finger and thumb	0 1 2 3	0 1 2 3
13	Ball bearing, held between middle finger and thumb	0 1 2 3	0 1 2 3
14	Ball bearing, held between index finger and thumb	0 1 2 3	0 1 2 3
15	Marble, held between ring finger and thumb	0 1 2 3	0 1 2 3
16	Marble, held between middle finger and thumb	0 1 2 3	0 1 2 3
		Subtotal ____/18	____/18
	Gross movement subscale		
17	Hand to behind the head	0 1 2 3	0 1 2 3
18	Hand to top of head	0 1 2 3	0 1 2 3
19	Hand to mouth	0 1 2 3	0 1 2 3
		Subtotal ____/18	____/9
		Total ____/57	____/57

Figure 7. Action research Test Scoring Sheet [5].

These exercises use different elements, such as various sized wooden blocks, a cricket ball and other objects with different sizes and shapes. The position in which the patient has to perform each task is also defined as seated upright without leaning forward or moving sideways, with the body in contact with the back of the chair and head held in neutral position.

Main problems with ARAT have to do with the need of a human examiner to assess the score based on their subjective observations, which can give raise to interoperate variability.

2.3.3 Fugl-Meyer scale

Fugl-Meyer (FM) scale is a "quantitative evaluative instrument for measuring sensorimotor stroke recovery, based on Twitchell and Brunnstrom's concept of sequential stages of motor return in the hemiplegic stroke patient" [12]. (See **Figure 8**).

The scores are directly correlated to the extent of corticospinal damage. With several evaluations using this scale over time, physicians can evaluate the patient's progression and recovery of motor function. The minimum detectable change using this scale is about 8% of the maximum score. Although this is precise enough for early stages, when high-performance patients that are further up the recovery path need to be assessed, the FM scale may lack precision in the evaluation of fine-tuned movements [23].

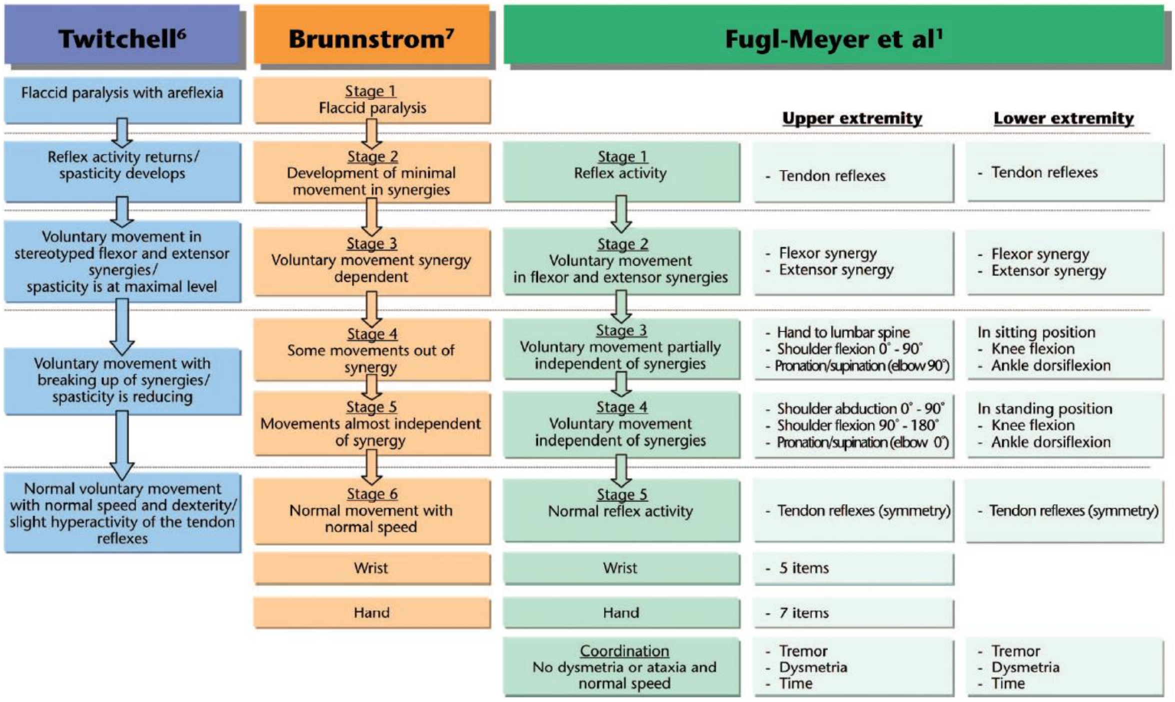


Figure 8. comparison of sequence of stepwise recovery described by Twitchell and Brunnstrom with the stages and scale used by Fugl-Meyer et all [6].

The FM scale is punctuated over a maximum of 226 points divided into 5 domains: motor function (from 0 to 100), sensory function (from 0 to 24), balance (from 0 to 14), joint range of motion (from 0 to 44), and joint pain (from 0 to 44). Each domain contains multiple items, each scored on a 3-point ordinal scale (0 = cannot perform, 1 = performs partially, 2 = performs fully)". [6]

This scale evaluates both upper extremity and lower extremity function for each of the 5 domains and takes about 30 minutes to perform. It is widely used and accepted in terms of sensibility, reliability and validity. However, in terms of responsiveness (evaluation of clinical change) it is not discriminative enough in severely affected patients who can not achieve the maximum score.

Some of the exercises evaluated for the distal upper extremity, which is what interests us the most, are: wrist flexion/extension with elbow at 0 and 90 degrees, firstly freely and then against resistance. Wrist circumduction, finger flexion, finger extension, extension of MCP joints, flexion of PIPs/DIPs, thumb adduction, thumb opposition and grasping different objects such as cylinder and tennis ball.

Both the ARAT and Fugl-Meyer scale present an important drawback due to their ordinal quantification, since they do not discriminate between the patient achieving the goal movement thanks to behavioral restitution or thanks to compensation. [24]

2.3.4 Wolf Motor Function Test

Wolf Motor Function Test (WMFT) is a test designed to assess motor ability of chronic patients with upper extremity motor deficits, widely used on patients who have suffered from stroke. It assesses both distal and proximal upper limb function. It is more useful for patients with higher functioning than for those more severely affected or have not yet experimented spontaneous recovery. This is why current versions of the test use 14 of the original 17 WMFT and have incorporated two forms of each task, these being two levels of difficulty for patients in different conditions to perform. [26]

In opposition to previously explained scales, where grades are within a range of scores and they are assessed based on the quality of the performance, hence by the subjective observation of the physician in charge, WMFT exercises' are graded based on the time required to perform each task, being 120 seconds the maximum allowed. The median of such time for each exercise is calculated to give a final score.

Precision is sought by defining a specific position of objects and movements to be placed and provides with a template to guarantee so. This applies for both the desk surface, the chair and the floor, whose size, coordinates and relative positions between each other and the patient are strictly described.

All exercises are videotaped for a panel of physicians to analyze them afterwards, and to have a record of patient's evolution pre and post treatment.

Patients receive visual and verbal instructions, with every exercise being precisely defined in terms of the setup, the task to be performed and the instructions to be given. These exercises are simple daily tasks such as placing the forearm on one side of the table or of a box, extend the elbow with and without weight, place the hand on a table or a box with and without weight, reach and retrieve, lift a can, a pencil and a paper clip, stack checkers, flip cards, grip strength, turn a key in lock, fold a towel and lift a basket.

2.4 Prognosis and rehabilitation

2.4.1 Prognosis

We understand prognosis as a prediction of the outcome of a patient after suffering from a medical condition. In the case of stroke patients, prognosis is very variable depending on the severity and extension of the lesion, its location and the time passed from the starting of the stroke until treatment is received. Other factors such as age and overall health status can also affect patient's ability to recover.

The outcome of a subacute stroke can range from total recovery to severe affectation of sensorimotor and/or cognitive function.

This Thesis focuses on the motor function loss of the distal upper limb as a consequence of subacute stroke, where some movements and functions have been found to be key in the evaluation and prediction of evolution in motor function recovery. Some of said movements are:

- Grip strength. A positive evolution of this task implies that the patient is responding positively to the therapy.
- Speed and extent of isolated joint range of motion. Active range of motion early on predicts function at later time points. [23]

These parameters have been mentioned as some of the most widely used in clinical assessment, independently of the scale used.

2.4.2 Rehabilitation

Rehabilitation services are the primary mechanism by which functional recovery and reincorporation into normal daily life are achieved in patients who have suffered from stroke. These therapies include a broad variety of exercises and approaches that have limited the obtention of a standardized protocol and clinical conclusions. These approaches vary in duration, intensity, type of intervention and healthcare professionals involved, including doctors, rehabilitators or nurses [10].

After acute hospital admission for stroke, patients should have comprehensive assessment of body functions and structure, as well as the affectation in terms of limitations and symptoms. This can be done within the first 24 hours when the patient's situation is stable and allows it.

In order to properly plan the rehabilitation, it is crucial to understand the origin of the lesion, and which impairments are contributing to the patient's status. In the case of learned nonuse, interventions must be oriented towards potentiating excitatory plasticity. When the main problem is learned bad use, implying an exacerbated nervous response such as the one occurring in spasticity, the focus should be put in potentiating inhibitory plasticity. This rehabilitation needs should be assessed by an interdisciplinary team formed by rehabilitators, neurologists, occupational therapists and psychologists, amongst others [23] [10].

However, since these disorders evolve along with the patient and turn into their complementary, therapy should be constantly rethought during the process to match patient's need. Furthermore, disorders usually coexist and need to be treated independently [23].

At the moment, there is no single functional assessment with measurement properties that is used throughout the entire clinical course of stroke care (acute hospital, inpatient rehabilitation, and outpatient care) for tracking stroke rehabilitation outcome. Some of the movements to be analyzed are those related to normal capability of patient, which is known as ADLs (activities of daily life).This term refers to both simple and basic fundamental activities and more complex leisure-related activities.

Going back to our focus on upper extremity mobility affectation, this symptom happens widely in stroke patients and being one of the hardest functions to fully recover, as has been mentioned before. This is why it is one of the main points of focus for rehabilitation therapies. These rely on task-specific training, usually combined with many upper extremity interventions, with the purpose of restoring normal function by repeating certain movements.

The relationship between prognosis and rehabilitation is very important. In the case of a severely affected patient with an irrecuperable function due to the characteristics of the lesion, efforts should be oriented towards those functions that could be restored. In the case of patients with a good motor prognosis, efforts should be placed on these abilities in a quick and intense response, so that mechanisms like learned nonuse don't take place, and so neuroplasticity effects are still in full capability.

Considering different possible events happening along recovery, assessment aims also to predict them in order to prevent their appearance. Such is the case of previously mentioned spasticity, happening in the upper limb for 33% of patients admitted to rehabilitation within the first 3 months post-stroke. The strongest predictor of spasticity is severe proximal and distal limb weakness. Considering the huge cost associated with patients who suffer from spasticity, preventing it might not only have an impact on patient recovery and better outcome, but also on rehabilitation expenditure [10].

2.5 Virtual Reality and stroke

Virtual Reality has been defined as "the use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear and feel similar to real-world objects and events" [27]. Virtual Reality (VR) and Augmented Reality (AR) are concepts included within the "Reality-Virtuality Continuum", used to classify the different types of realities arising from virtualization. It goes from the real world to a completely immersive virtual world [28]. Whereas virtual environments are fully computer-generated settings with which the user interacts through an immersive device, AR is part of Mixed Reality (MR), where the physical environment surrounding the user is modified with virtual elements [29].

The value of VR devices sold is expected to increase from US$1.5 billion in 2017 to US$9.1 billion by 2021 [30], accordingly to the increase in use, applications and general popularization of this type of technology.

Some of the uses that are being conceived for AR and VR can be found within the healthcare field. One of the applications where these technologies are expected to have the most impact is neurorehabilitation. By choosing the appropriate devices, traditional techniques can benefit from new interactive simulations that increase patient engagement and performance on different tasks. Most VR systems provide with visual-auditory feedback, but they may also include haptic, vestibular and olfactory stimuli [31].

The specific applications for which VR is being tested in this field go from cognitive impairment to motor disorders. Main advantages include patient encouragement and motivation, objective measures with a strict experimental control, possibility to personalize treatment and tests in a standardized way, the capability to progressively increase difficulty and complexity depending on needs and the possibility to give the patient more control over their therapy not needing to rely that much on practitioner's labor and reducing staff dependency.

Although price is getting lower fast, it is still a drawback for daily clinical applications. Low-cost VR devices are getting more common by the day, though clinical effectiveness of this type of devices has yet to be tested. Physicians are starting to adapt devices intended for gaming for clinical purposes. Such is the case of this thesis [27].

Although not much data has been collected on the implications of VR use on stroke patients, some findings suggest that tailoring manipulation of the visual feedback in virtual reality to the needs of the patient may serve as a tool for rehabilitation. Some examples of this ad-hoc approach are to create mirrors of the healthy member to stimulate brain response for the affected one, or presenting individuals with specific stimuli aimed at activating the cerebral region where the lesion is located. The most relevant application, in terms of proven effectiveness, was found to be arm function improvement and practice of activities of daily living for patients having suffered from stroke. [27]

However, further study needs to be done in order to extract significant conclusions on the advantages of virtual reality on the different domains of neurorehabilitation (cognitive, upper-limb function, march study, etc.). These studies will have to be aimed at stroke patients specifically and take into consideration different population characteristics such as age or gender. They will aim to understand the role that implementing VR systems, both based on current gaming applications and virtual environments specifically designed for each use case, and considering different therapies types, in terms of active or passive rehabilitation. Finally, the outcome will have to be measured by defining key performance indicators (patient recovery time, dose and time of therapy…) and the obtained results both in cognitive recovery and the World Health Organization's International Classification of Functioning, Disability and Health, used broadly to classify outcome of clinical practices [32].

This systematic review should be based on the PICO process, used in evidence-based practice to frame and answer a clinical or health care related question [33]. This abbreviation, as shown in **Figure 9**, stands for the main points of focus: Population, Intervention, Comparison and Outcome.

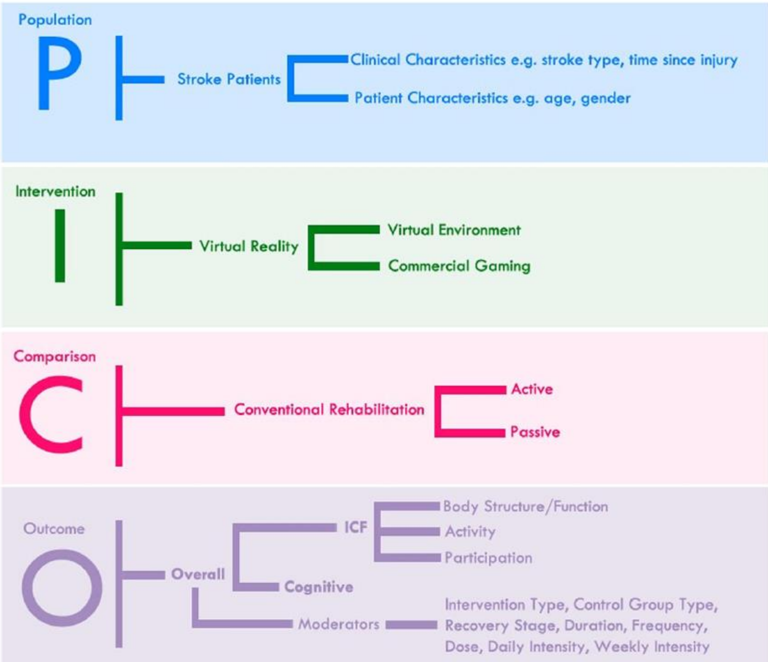


Figure 9. Question and the main variables included in the systematic literature review and meta-analysis [33].

3 Methodology

To accomplish the set goals, and after an understanding of the patient's and clinicians needs, it was decided that the most suitable technology for this project was the Leap Motion controller and an environment developed with Unity. A thorough analysis of why this technology was chosen and how it works is provided in section 3.1.

In section 3.2 we will see how the exercises were defined in the real world, following the recommendations made by neurologists who diagnose motor impairments of stroke patients. This will cover objective 2 of this MSc Thesis: "Definition of a series of exercises in collaboration with neurologists and replicate them in a virtual reality environment".

In order to implement these exercises in the virtual environment, it is important to understand the technical requirements that should be followed, in terms of optimal ranges of work and support systems for the patient, which are shown in section 3.3. This will accomplish objective 3: "Definition of the physical conditions for the appropriate performing of the exercises".

Finally, with all these inputs, the environment was developed in Unity using Leap Motion's virtual reality technology, as shown in section 3.4. This section achieves objective 5 of this MSc Thesis: "Development and implementation of a virtual reality environment".

The workflow followed is represented in the following schema (see **Figure 10**):

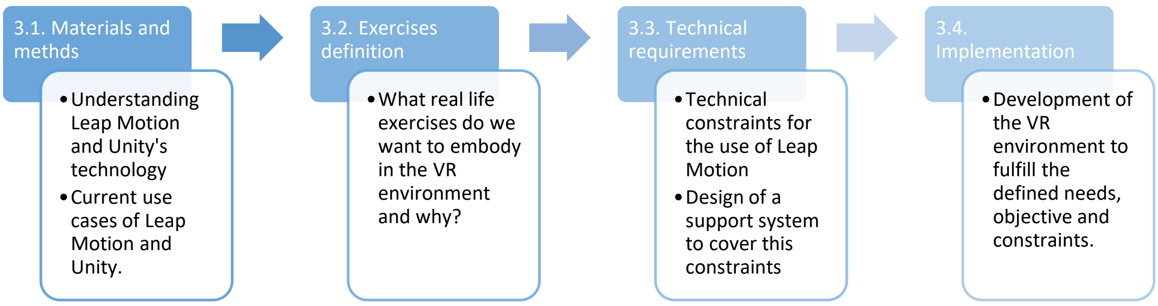


Figure 10. Outline of chapter 3 to show the methodology followed.

3.1 Materials and methods

3.1.1 Leap Motion

The Leap Motion Controller from Ultraleap, shown in **Figure 11**, is a low-cost and portable virtual reality device. It is commercially available through different websites at a cost of around 90€.

There are many reasons that made Leap Motion the optimal choice for this project. Firstly, Leap Motion covers the need required in terms of virtual reality: it creates a virtual replica only of the hands, which is the part we are interested in, and it is not immersive, which could imply a greater complexity and discomfort for the patient. Secondly, it is small and portable, so it can be used in the most convenient place each time. Moreover, it is a low-cost device commercially available, so its acquisition or price is not a drawback if this project was to be fully implemented at hospitals and increased in scale.

Finally, one of the key points for selecting Leap Motion was that it does not require any electrodes or gloves, as other VR systems involving the hands. Having to put anything on can be an impediment for patients whose mobility and strength of the hand are severely affected. Furthermore, the possibility of recording hands that are moving completely freely, allows to capture and analyze the way in which the hands move naturally, like in daily life situations, or like the doctors see them while diagnosing.

Technologically, the way in which Leap Motion registers the hands is through an optical mechanism. Leap Motion can track users' hands and reproduce them in an interface, so they can interact with a virtual reality environment in a lifelike experience. Some of its technical specifications include its 3D field of view (120x150º) and its high frequency refresh rate (120Hz), which makes it possible to obtain a real time reproduction of hands' movement [4].

Figure 11. Ultra Leap Motion Controller [4]

It is important to understand the way it works, the classes it provides and the way it interprets physical realities such as hands and fingers. Variables related to these classes are important as well. They keep important and useful information that will be used in the development of the module. [34]

Leap motion uses a coordinate system with the origin on the center of the device and the axis oriented as depicted in the following picture (See **Figure 12**).

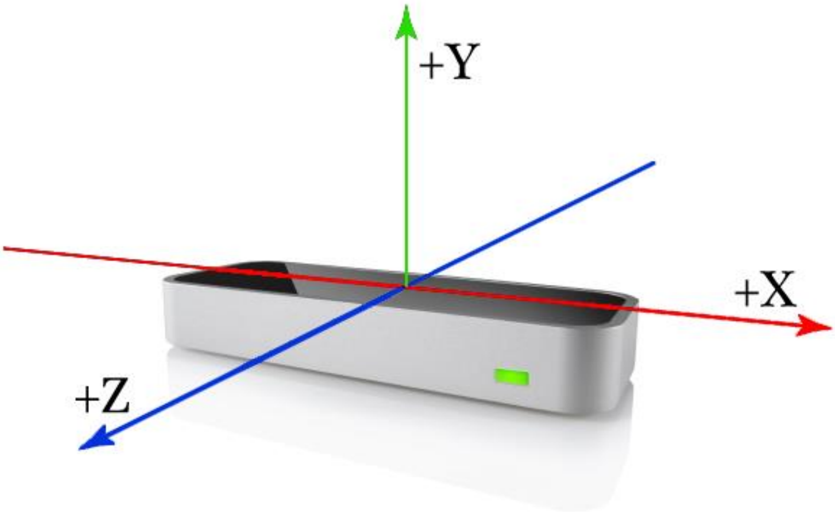


Figure 12. Leap Motion coordinate system [35].

Tit measures the following types of variables:

- Distance: millimeters
- Time: microseconds (unless otherwise noted)
- Speed: millimeters/second
- Angle: radians

The Leap Motion controller continuously registers and tracks hands and fingers located within its field of view. Each update of this information is saved in a frame of data, which is also represented in its corresponding object: the Frame. The Frame object is considered the root of the Leap Motion data model.

<u>HANDS</u>

The hand model (see **Figure 13**) represents the hand in the physical space through several parameters such as a unique identification number, the position of the hand center from each frame, the arm to which it's attached and the list of fingers corresponding to that hand. Hands are represented by the Hand class. [35]

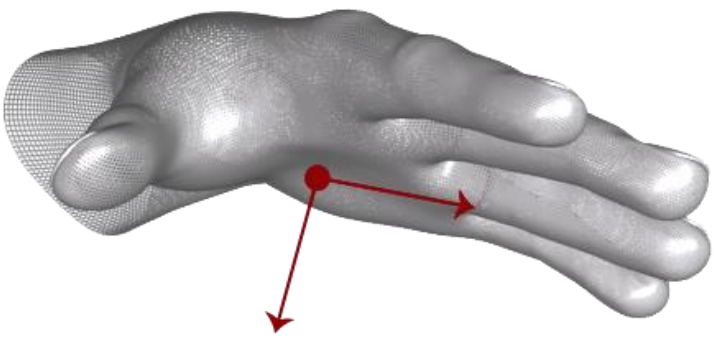


Figure 13. representation of hand model [35].

Leap Motion recreates the hand even when it does not detect certain parts. It relies on a predefined internal model of a human hand and uses predictive approaches to reconstruct it whenever it is not visible. In this way, the controller guarantees information of the five fingers, although this information is the most reliable when the whole hand and finger's shape is visible.

FINGERS

For a detected hand, each finger is tracked, and whenever a part or a whole finger is not visible, it is reconstructed following the same internal human hand model as before (see **Figure 14**). Each finger is identified by its name: thumb, index, middle, ring, and pinky.

Figure 14. representation of fingers model [35].

3.1.1.1 Leap Motion use cases: developers

Ultraleap's Leap Motion Controller uses two image sensors plus infrared LEDs [4]. In this way, the user can interact with the interface life-like while being tracked with sub-millimeter accuracy (see **Figure 15**). The potential applications for this device are plenty, and some of the cases for which it is intended, as stated by Ultra Leap, are: "entertainment: (location-based VR/AR experiences, arcades, amusement parks), healthcare (stroke rehabilitation, training, mirror, medical imaging, lazy eye treatment), therapy and Education (anatomic visualizations, hands-on learning), personnel training (flight simulators, complex computer systems), industrial design and engineering (automotive, assembly lines, facilities management), robotics (bomb disposal, telepresence, robotic controls, AI-assisted teaching) and global team collaboration" [4].

Figure 15. Leap Motion's interface [36]

Other current uses include games that developers are designing. Some of these are going towards medical applications, such as:

- **Vivid vision**: curing lazy eye with VR + Leap Motion [37]. This project aims to take advantage of the brain's capability to retrain by creating an environment for patients with lazy eye. Through these exercises, patients practice hand coordination skills. This technology, that is already being tested in eye clinics, provides a new and fun way to cure strabismus, amblyopia and other disorders of binocular vision.

- **Itadakiamasu!:** this environment was created to allow interaction between humans and VR animals [38]. These animals would have the role of therapy animals, currently used for reducing anxiety and depression in psychiatric patients. It also allows to benefit from this company when patient's circumstances do not favor having a company animal. By creating animated characters, this project aims to develop patient's emotional response to them and create a bond that would ease their symptoms, like a real therapy pet would do.

- **CadaVR:** CadaVR is a learning environment designed for medical and non-medical students who do not have access to real-life cadavers while learning, since cadavers are expensive, difficult to get and its availability is limited [39]. CadaVR replicates a beating heart allowing students to interact with it by grabbing and scaling it. Plus, they can complete certain tasks as if they were in an actual classroom.

- **ASL Tutor:** this project created a sign language translator with a Leap Motion controller [40]. Applying machine learning to the hand representation, they aimed to translate a certain hand position into a letter of the alphabet. The final result was a game where users could learn sign language by mimicking a hand position showing on the screen through Leap Motion.

- **Motion Savvy:** this project is similar to ASL Tutor, with a further development. It already has a free app available to play and learn sign language [41].

3.1.1.2 Leap Motion use cases: clinical studies

Some clinical research studies have been done in order to evaluate the usefulness of Leap Motion in the clinical environment, specifically in neurorehabilitation for subacute stroke patients. Such is the case of the study performed in China Rehabilitation Research Center at Beijing Boai Hospital, China [3]. In this study, selected patients, who had suffered a stroke for the first time in the last 4-24 weeks with mild to moderate affectation of the upper extremity, were faced with a series of tasks. These tasks were aimed at developing their pinching, grasping and individuating motor skills of fingers, while recording improvement of performance in terms of precision, strength, time required or movement range. These exercises were gamified in order to create engaging challenges, such as petal picking or piano playing. Patients were divided into two groups, one of which received twice the amount of conventional therapy and served as control, whereas the other received both conventional therapy and virtual reality training. The frequency of the therapy was 45 minutes, once a day, 5 times a week for 4 weeks. After this period, both groups experimented significant improvements in their motor functions, but it was greater in the experimental group, and time required to perform tasks was shorter. Plus, fMRI showed a greater activation from the ipsilateral or bilateral to contralateral cerebral regions. No side effects were detected in either group, but patients stated that the Leap Motion-based therapy was more enjoyable. In summary, the results of this study showed that the use of this virtual reality method could slightly improve results in rehabilitation and appears as a promising tool as adjuvant rehabilitation intervention.

Another similar study aiming to test Leap Motion's technology on people who had suffered from ischemic stroke took place at Bolu Abant Izzet Baysal University, Physical Therapy and Rehabilitation Hospital, in Turkey [42]. This study included 65 patients whose stroke had taken place in the last six to twenty-four months. As well as in the study in China, here patients were randomly divided into a control and a VR group. The virtual reality approach consisted in the Leap Motion device integrated with virtual reality glasses and headphones for a fully immersive virtual reality experience. They wanted to test this way in opposition to other studies performed in the field, such as the one explained above, that use 2D virtual reality experiences. A key point they wanted to focus on that other studies did not analyze was tracking finger motion through the device. The patients in the VR group performed a series of task-oriented exercises as depicted in **Figure 16:**

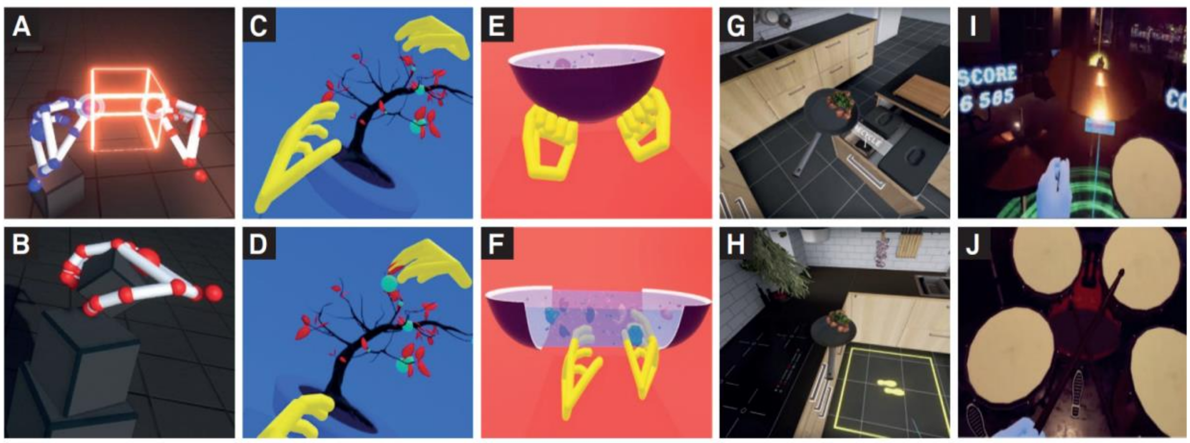


Figure 16. exercises performed by the patients in the VR group [40].

1. **Cube handling game:** gripping function evaluation. Patients interacted with a virtual cube as if it was lifelike.

2. **Decorating a tree:** facilitate all hand motions including complex ones.

3. **Picking up vegetable from a bowl and putting them back:** same purpose as the previous exercise.

4. **Kitchen experience:** stimulation of forearm supination and pronation and combination of complex movements.

5. **Drumming game:** exercise to randomly separate movement of upper extremity flexion and abduction.

These exercises are aimed at following the general guidelines of motor learning in the case of stroke rehabilitation, which puts the focus on the following parameters: "repetitive, and varied practice; progression of task difficulty; problem solving and error correction; motivation; and the frequency and quality of feedback" [42].

The frequency of administration of rehabilitation for both groups was of three days a week for six weeks, with sessions lasting 60 mins each. The control group had the same task-oriented exercises oriented in a traditional way. They also included some VR exercises but only as a visual stimulus, with no upper extremity interaction.

The primary outcome was measured with the Fugl-Meyer scales. Secondary outcomes were measured with other clinical scales (such as ARAT) and others used for evaluating independence of patient on the daily life.

Prior to the results being examined, no significant difference was observed in the baseline characteristics of each group. After the study, both groups experimented a significant increase in their test results. When the scores of both groups were compared pre-test and post-test, there was a clear difference in favor of the VR group. The increase before and after therapy in the different test scores was significantly bigger for the VR group, indicating a more effective therapy when immersive environments are used.

3.1.1.3 Leap Motion use cases: Companies

On another side of clinical applications, and although most uses of Leap Motion in the clinical environment are still in research stages, there are some healthcare companies starting to incorporate this technology to the solutions they offer. Two of these companies are:

- **Evolv:** this company has created the first virtual rehabilitation software to be classified as a medical device and to obtain the CE marking: VirtualRehab Hands [43]. They are part of the Virtualware group, who creates real-world solutions using the latest in immersive and interactive technologies [44].
  VirtualRehab Hands uses Leap Motion technology to create a telerehabilitation tool of fine motor skills of the hands [45]. The activities include finger flexion, extension, abduction and wrist ulnar and radial deviation. The patient, for which the exercises are tailored and

personalized, holds their arm on a physical support (see **Figure 17**) in order to complete the tasks correctly. They include three modules: Assessments, Exercises and Exergames.

- Through the **Assessments** module, clinicians can keep track of patient's progress remotely. These assessments include four different wrist range of motion measurements represented in a graphic way.

- The **Exercises** module allows patients to perform certain tasks guided by a virtual coach who provides real time feedback. The exercises correspond to the four wrist range of motion previously assessed.

- The **Exergames** module create a gamified environment where the patient can do their rehabilitation exercises. These exercises are tailored individually depending on the specific needs. There is a set of eight exercises for fine motor training.

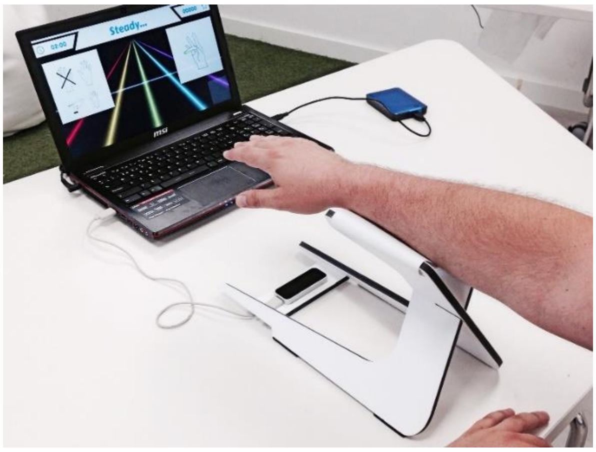


Figure 17. Evolve's arm support [45].

- **TedCas:** this company creates medical technologies based on contactless interfaces [46]. They have three main products: touchless interface for the control of medical information in a sterilized environment; 3D images for medical training and preoperatory planning; and personalized software for patient's following, remote communication and verification lists.
  Out of these three, all aiming to include VR/AR in the medical world, the one that uses Leap Motion is the first one: TedCube (see **Figure 18**). This plug-in device allows touchless control of patient's information while at surgery, so that no assistance is needed. It is compatible with the most popular sensors in the market, one of them being Leap Motion [47].
  It does not require to be certified as a medical device by the FDA but complies with Medical Device Class I [47].

Figure 18. Original TedCube with auxiliary screen [47].

3.1.2 Unity

Unity is an environment designed for the development of 2D and 3D applications, games and programs [48]. Unity's environment follows a hierarchized structure of projects and scenes that the developer works on. It provides plenty of already-created features that can be incorporated into a project by downloading packages. These packages may include different assets that can be used, such as objects called prefabs, scripts or environments. Besides this interface, used mainly to define the structure of the application, Unity relies on C# programming to define the actions of the game: interaction between objects, scene changes, data management… C#, managed through scripts created on Visual Studio, is a language with two possible focus: object-oriented and data-oriented.

Object-oriented programming uses objects charged in the Unity environment to define variables and functions that will mark progress of the game or application.

In our case, the most important objects will be:

- Patient data: introduced at the beginning of the session. Clinical record number or number assigned to the patient within the study.

- Hand controller: representation in the Unity environment of the Leap controller. This is the object to which the scripts will be attached, so that we can extract the desired information depending on the exercise (scene).

3.1.2.1 Unity use cases

The main use of Unity Engine is, as previously mentioned, game development. It is the environment used to create 50% of games across all platforms, 55% of new mobile games and 60% of AR/VR [48]. The content created with Unity has reached 3.3 billion devices in the last year and there has been 37 billion installs of content made with Unity [48]. 100% of all countries have Unity users [48].

Besides its traditional focus on gaming, which has also recently incorporated AR and VR, Unity has other possible applications that are already being used. These applications can be achieved thanks to Unity's openness, that allows the integration and data import from multiple sources and platforms.

Some of Unity's other uses are [49]:

- **Interactive experiences**: such as those found at restaurants with interactive menus, airports with digital information points…

- **Film previsualization**: recreation of a cinema scene to preview its final result.

- **Architectural visualization**: thanks to its 3D visualization and integration of complex structures, Unity allows to visualize plans for buildings and engineering projects.

- **Animation**: real time rendering of animated films is surging as an opponent for traditional animated film making. However, Unity is also used for traditional animation movies, since it offers high power graphical capabilities and a specialized editor for film making.

- **Simulations**: recreation of real-life environments for training of specific groups such as the military or medical students. For example, medical students can learn safely and face different challenges that can happen in a medical environment.

- **Anatomy study:** Unity's graphic capability can be used to render anatomical structures and make them interactable. It also provides the possibility of simulating 3D live organs instead of having to rely on 2D images or cadavers' organs.

Besides these fields of application, there are indeed companies dedicated to the development of environments through Unity. Such is the case of:

- **Kognito:** this company creates virtual simulations were human models recreate human-like reactions and emotional responses for specific cases. They have multiple uses for them, but some of them are medical training of communication with patients, detection of mental problems at primary care, preventive talks with adolescents or interactions in the emergency room [50].

- **Kerbal Space Program:** this project developed by the company Squad, uses a game-like approach to allow users to plan and recreate their own spatial mission. It has a mixed focus of playing and learning, allowing simulations of launching spaceships that the player has built [51].

3.2 Exercises definition

In this section, we will cover what exercises were chosen in consensus with neurologist's to replicated in the VR environment.

First step to define the exercises and modules to develop is to understand how doctors operate while diagnosing and assessing severity of the disorder. As previously mentioned, apart from the NIHSS scale, they perform a general overview by exploring muscular balance, that analyzes mobility and strength. The exercises they perform on stroke patients on the hand are described below. It is important to note that, in distal exploration, which is the one that interests us, exploration must be done isolated from the rest of the arm's movement.

The chosen exercises to be implemented on the module are taken out of the Fugl-Meyer scale that doctors consider the most important and that evaluate distal upper limb with no intervention of external objects. These, as mentioned before, are: wrist flexion/extension with elbow at 0 and 90 degrees, firstly freely and then against resistance. Wrist circumduction, finger flexion, finger extension, extension of MCP joints, flexion of PIPs/DIPs, thumb adduction, thumb opposition. [12]

Other way to explore motor function is through muscle movement oriented to specific tasks, such as object translation. This can give an estimation of precision, pinching and maintenance of function. This means that different levels of affectation can be seen if the patient is able to grab an object, precisely locate it at a certain place and keep a holding situation without losing force and dropping it. Grabbing objects using the whole fist is also useful as an indicator of patient's functionality.

Two different modules have been defined to be implemented within the monitoring system:

- **Module I**: **traditional evaluation.** Exercises in this module will emulate regular evaluation tasks performed by doctors and rehabilitators during routine explorations. Only a few of the most representative and easiest modelized exercises have been chosen. The only difference with traditional evaluation will be that the movement will be tracked by Leap Motion and that the patient will follow the instructions shown on the screen. The purpose is to quantify the precision of Leap Motion while tracking these movements in a later analysis, to compare them to a clinician's observation capacity.

- **Module II** : **VR interaction.** Exercises in this module will try to create a gamified environment where patients have to complete a task-oriented movement. These movements will include interaction with virtual objects that the patient will have to grab and move to a specific place. The purpose is to analyze the added value of gamification and virtual interaction in the patient's evaluation process, in terms of engagement and motivation. Moreover, data will also be analyzed to extract relationships between patients performance in the game and the abilities that were being evaluated (grabbing, pinching,…).

For both modules, the extracted data with patient's diagnosis is processed to be compared with their health status, pursuing the main goal of this MSc Thesis: to create an objective diagnosis tool for hand evaluation in stroke patients.

3.2.1 Module I: traditional evaluation exercises

In what follows, the different actions of module I are defined.

1. **Finger extension (separation):** this first exercise in intended at evaluating fingers mobility altogether. The patient should place the hand on the horizontal plane over the controller and open the hand separating the fingers as much as possible, as portrayed in **Figure 19**.

Figure 19. Exercises 1 and 2 beginning and end. Left and right fingers extension.

2. **Thumb movement:** the thumb is analyzed separately and more thoroughly due to its importance. Specifically, it will consist in an analysis of abduction, adduction and pinching. With these three exercises, the thumb's mobility will be evaluated in every direction, and in a task-oriented way as is pinching.

    a. **Thumb abduction and adduction in the horizontal plane (XZ):** this exercise evaluates thumb's lateral abduction and adduction capability. The patient should place the hand on the horizontal plane over the controller and move the thumb on this same plane, keeping the rest of the fingers closed, as depicted in **Figure 20**.

Figure 20. Exercises 3 and 4 beginning and end. Thumb abduction on the horizontal plane.

b. **Thumb abduction and adduction in the vertical plane (YZ):** this exercise evaluates thumb's vertical abduction and adduction capability. The patient should place the hand on the horizontal plane over the controller and move the thumb perpendicularly to the hand, towards the controller. It is exemplified in **Figure 21,** although pictures were taken from what would be a lateral view so that the reader could appreciate thumb's movement.

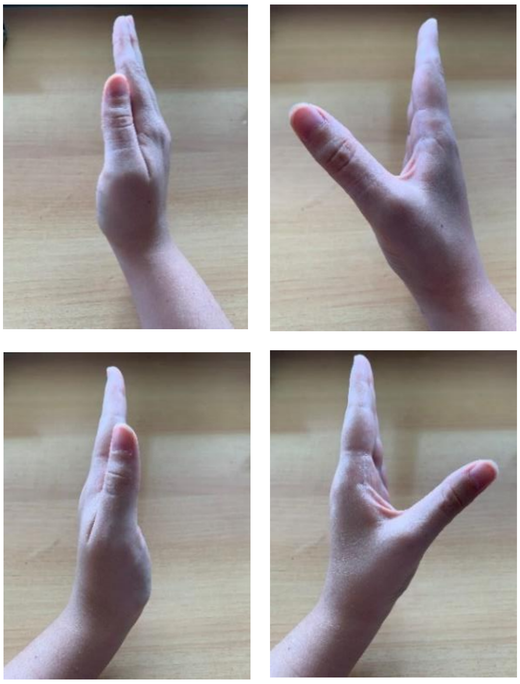


Figure 21. Exercises 5 and 6 beginning and end. Thumb abduction on the vertical plane.

c. **Pinching:** pinching movement is the most important one when evaluating patient's motor function because of its implications in daily life. This movement allows the patient to grab objects, and the ability to do so can mark the difference between an independent subject or a dependent one. The way in which the exercise should be performed is shown in **Figure 22.** The patient should place the hand on the horizontal plane over the controller and perform a pinching movement as they would normally do.

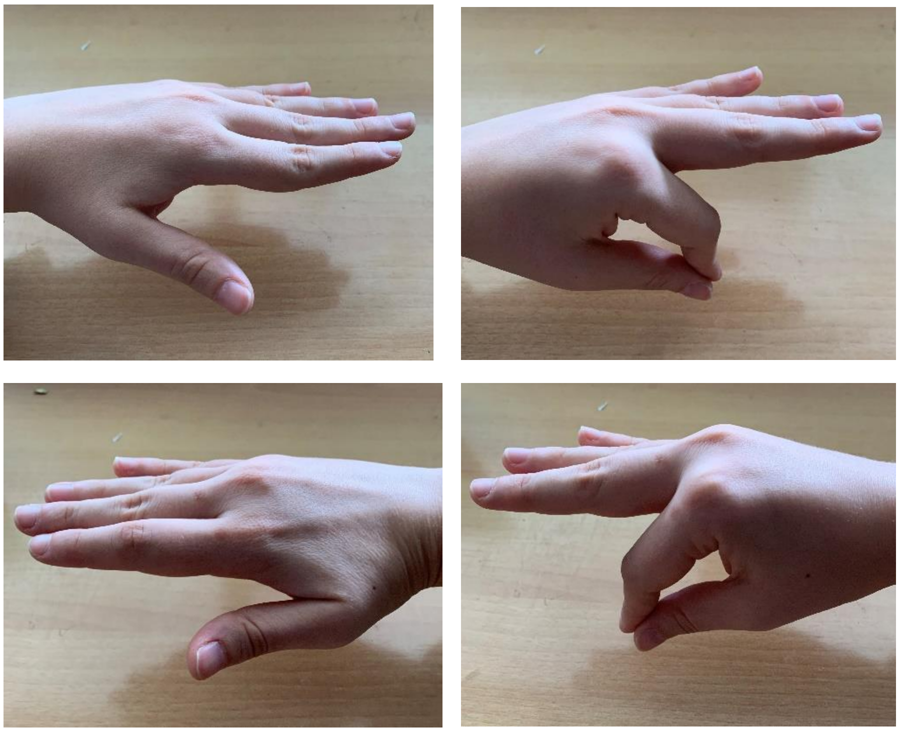


Figure 22. Exercises 7 and 8 beginning and end. Pinching.

3.2.2 Module II : VR Interaction exercices

In what follows, the different actions of Module II are defined.

1. **Drag cubes to specific place:** this exercise will measure patients' ability to perform a precision movement, hold a position over time and perform a preestablished trajectory.
   As the exercises in Module I, this one will be done firstly with the left hand and then with the right hand, to have information on both separately.
   The way in which the patient should perform this exercise is freer than the previous ones, since it involves grabbing virtual objects (the cubes) and dragging them towards a specific point in the VR space (the targets). This time, it is important to consider we are working with the hypothesis that this will imply a learning curve for the patient to achieve the goal, and therefore the applications of this game can be more oriented towards rehabilitation than diagnosis.
   In **Figure 23**, we can see the starting point of the game. More details on the process of the game is shown in Section 3.4.

Figure 23. Module II: interaction with VR game.

3.3 Technical requirements

The upcoming section is key to guarantee a proper development and later use of the VR environment. Firstly, because understanding how Leap Motion works and its technical specifications will help assure that the obtained results are the best possible. Secondly, because, since this MSc thesis is focused on stroke patients, a support system is needed, and this system should take into account Leap Motion's working requirements to ensure the patient is always complying with them.

Leap Motion defines an optimal range where the hand is fully seen and the interaction with the interface is guaranteed. Although the field of view is wider than this box and the internal hand model allows to fill in whatever hand parts that are not possible, it is important to keep the patient's hand within the optimum volume.

The interaction box is defined in **Figures 24 and 25.** This box is a 235x235x235 cm cube place at a height of 20 cm over the center of the controller. Outside this box (red cube in **Figure 24**), the hands are still visible as long as they are within the green pyramid seen in **Figure 24**, but the behavior is not optimal.

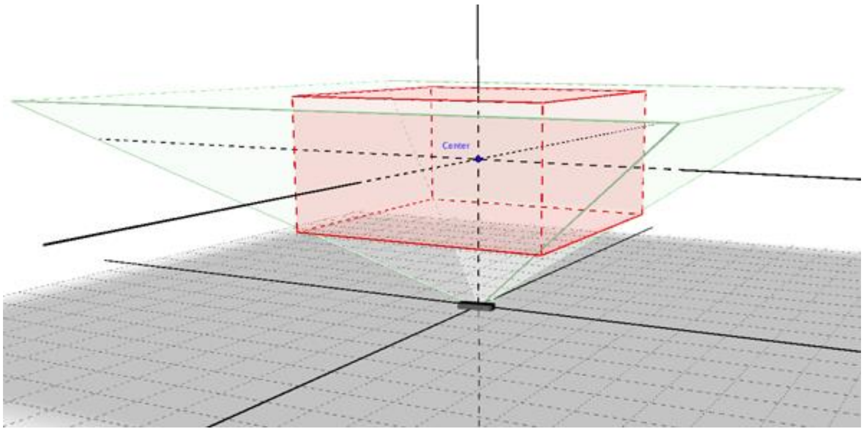


Figure 24. Interaction Box [52]

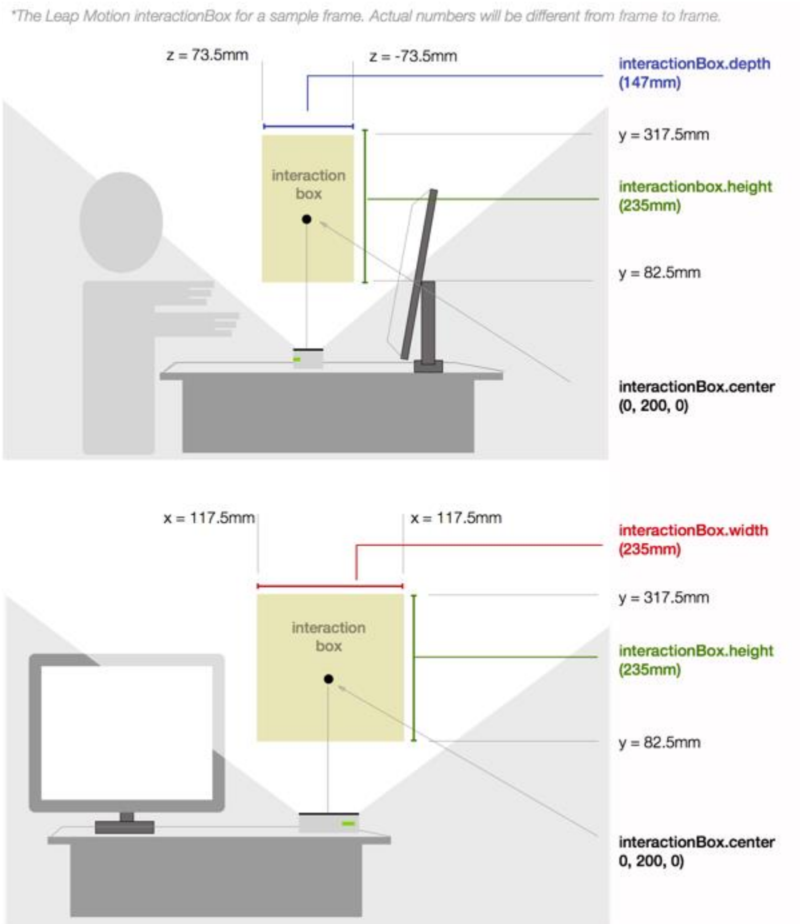


Figure 25. Interaction box specifications [52]

These requirements make it necessary for a support system to be developed[2]. This system should be developed to cover the following requirements:

- Allow hand and wrist movement over Leap Motion controller and within the interaction box.
- Considering that, in most cases, one of the patients' arms will be affected, the system should be designed considering a lack of force and tone on the patient's part. Moreover, since the purpose is to evaluate hand motion, the arm and shoulder should be at rest so that no compensatory forces help the movement. Therefore, the second requirement is that the support holds the patient's weight and guarantees that they can keep the required position in a relaxed position.

A simple sketch was designed with TinkerCAD to get an idea of how this device should be as depicted in **Figures 26 and 27**. In them, we can see how the exercise should be performed and the measures of a support system that optimizes the location of the hand in the interaction box. The exercises were implemented keeping this in mind, and the tests were done following this distribution.

The forearm should be placed on top of the support in a stable way, with the hand standing out the edge so that it is placed right over the center of the controller and in the middle of the interaction box. It is recommended that the box and controller are placed aligned with the center of the screen where the game will show, to improve performance and simulating a more real experience.

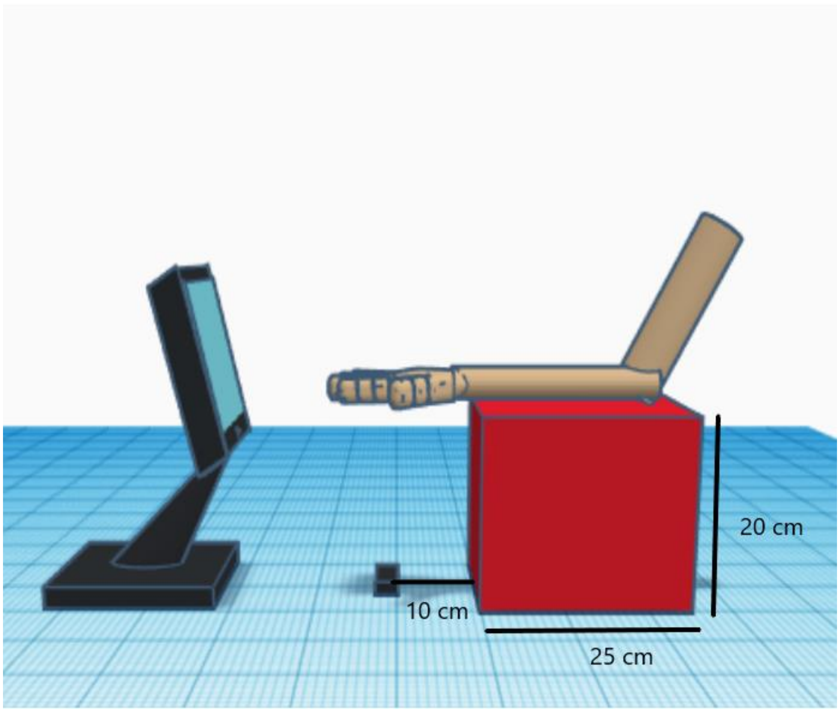


Figure 26. Simplified design of a support system for stroke patients. Lateral view.

[2] It is important to note that the prototype was developed within the Covid-19 [7] restrictions that did not allow us to develop a more sophisticated and final version of the support system.

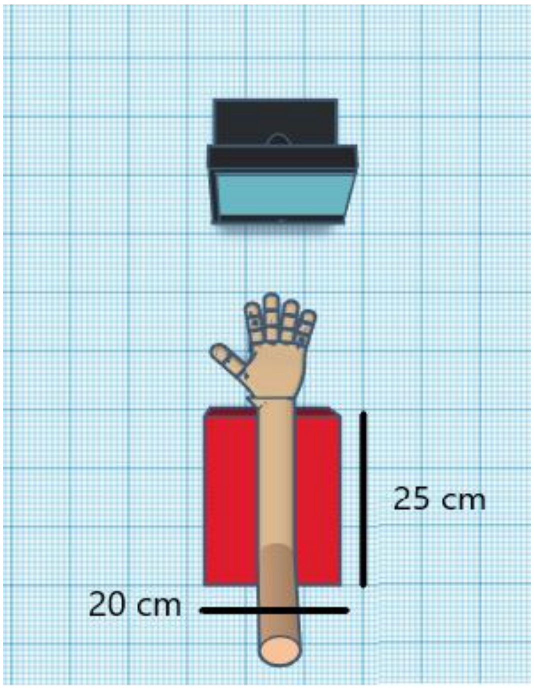


Figure 27. Simplified design of a support system for stroke patients. Superior view.

<u>SUPPORT MEASURES:</u>

The specific measures of the designed support system are the following:

- Length: 25 cm so that the forearm can rest comfortably during the exercises.
- Height: 20 cm so that the hand is always within the interaction box and close to the interaction box center (0,20,0).
- Width: 20 cm so that the forearm can rest comfortably during the exercises and that the range of motion is confined within -10 and +10 in the x axis, i.e., within the interaction box. The center of the box should be aligned with the center of the Leap Motion controller.
- Distance to Leap Motion controller: 10 cm so that the hand rests over the center of the controller, and it does not move further from -8 cm and 8 cm, which is approximately the depth of the interaction box.

<u>SUPPORT MATERIAL REQUIREMENTS</u>

The box should be made with a compact and resistant material that does not bend nor move when the arm is resting on it. Although a system might appear as stable, if it is hollow and the walls are not rigid enough, the controller detects a certain vibration that translates into an instable hand on the interface.

This is the reason why empty boxes were discarded for this homemade prototype. In the case of using them, they should always be filled with a compact material in order to avoid said vibrations.

It would be recommendable as well to design the box so that it includes a comfortable armrest on the top surface, so that the patient does not experience any discomfort during the exercises.

Whenever this system is tested in the clinical environment, some other modules could be found necessary. A possible one is an arm strap to avoid the patient to move the arm to compensate those hand movements that are more difficult or that he can't perform correctly.

Probably, the best way to iterate and prototype would be 3D printing different designs, until the optimal one is achieved. A good example of a similar system implemented by another company is the one developed by Evolv, shown in **Figure 17.**

CORONAVIRUS PROTOTYPE

The previously mentioned prototype was not developed due to the Covid-19 situation [7]. No 3D printers nor fabrication materials were available during lockdown, so a simple support system was designed to hold the arm at the required height and distance from the controller.

This box was a piece of carton covering a series of books, so that it would be stable and resist the weight of the arm without giving in. The design was the one shown in **Figures 26 and 27**, and the outcome was the one shown in **Figure 28.**

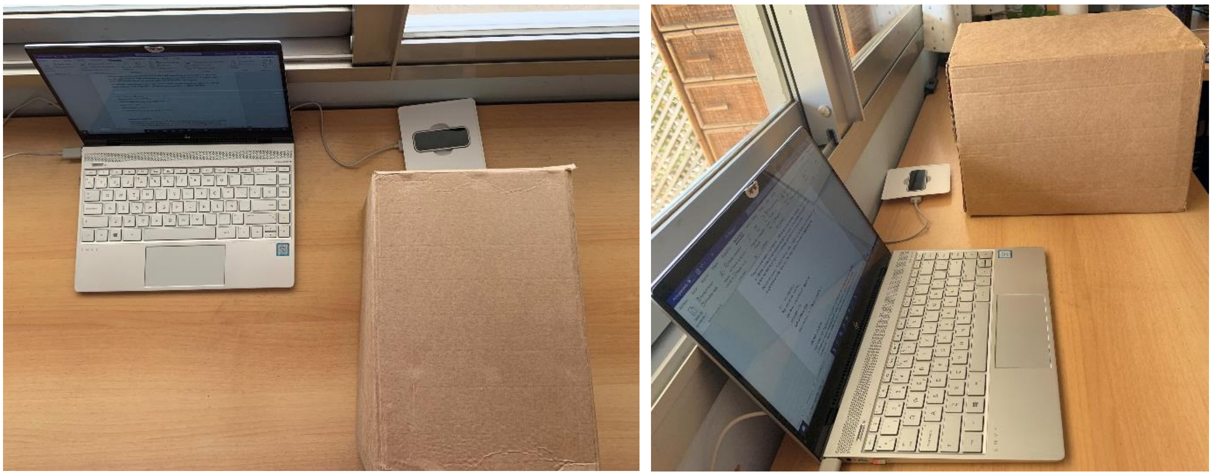


Figure 28. Prototype of the support system in the confinement situation of Covid-19.

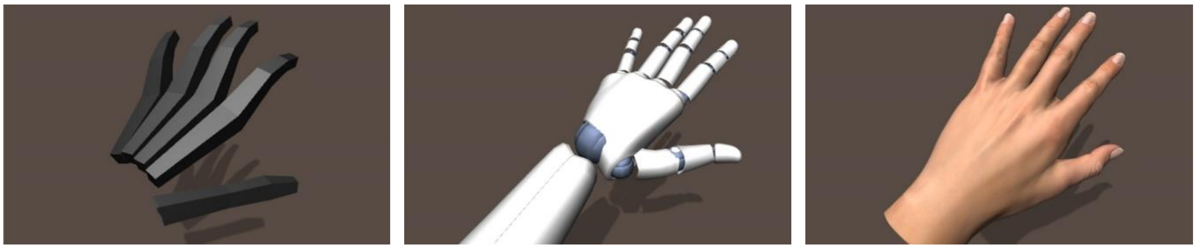
3.4 Implementation in Unity and Leap Motion

After choosing the most appropriate technology, understanding how it works and designing the support system with which patients will work, the next step is to implement the exercises defined in section 3.2. in Unity.

The way in which Leap Motion integrates with Unity relies on a key object, which is the hand controller object. The hand controller is the element that represents Leap Motion's controller in the scene, and depending on where it is placed, hands will appear in a different place during the game. This is an important point, because objects conceived to be interacted with should always be placed considering the range in which the hands will appear and move. To extract information on the hand controller and to modify its behavior, scripts of code are attached to it. This code has been uploaded to GitHub[3].

[3] Repository: https://github.com/Robolabo/strokeHandMotion

The *HandController* class controls the acquisition and application of tracking data to the hands and fingers. It has two prefabs that must be chosen: Hand Physics Model and Hand Graphic Models. The first one determines the way in which Leap Motion registers the hand, which is why we chose a Physics Hands Model, in particular Rigid Round Hand. The second one determines the way in which the hand is represented on the scene [53]. It can be realistic or robotic, with many different ones to choose. We chose one that was in between realistic and robotic, since it has the shape and movements of a real hand, without trying to put unnecessary details, such as skin, that the user may not recognize as their own. The chosen model was Clean Robot Full, but choosing another would not alter the obtained results, only the user experience. We can see different types of Hand Models in **Figure 29**.



(a) **(b)** **(c)**

Figure 29. Different hand types offered by Leap Motion. (a) PolyHand (Procedural Hand), (b) Clean Robot Full (Component Hand) and (c) Human model (Rigged Hand) [53].

Once the hand controller is set, the rest of the environment is constructed around it. In the case of module I, this process is quite simple because the purpose of it is simply to record the hand's movement, so no extra objects need to be added on to the scene. For this case, only the canvas is implemented, which includes the buttons to go back and forth, the pictures exemplifying the exercise to ease the process for the patient, and a brief explanation on what has to be done.

In the case of Module II, where other objects are used, we need to make these objects interactable with the hand by adding the corresponding physics component Box Collider. The way in which colliders work in Unity is that objects that have it enabled can interact between them as objects in real life would. In the case of Leap's hands, they are interpreted as collider objects, so if they encounter an object, they will displace them. Considering that in this module we want patients to grab the object, the Physical Hand Model was changed over to Magnetic Pinching because it allows to attract objects to grab them, making it much easier and reducing the learning curve. The platforms are normal Unity objects fixed onto the floor, so the hand does not displace them when passing near them.

Finally, as in Module I, exercises in Module II have a canvas containing the environment's details, which in this case includes a counter as well as the buttons and explanations. The scene must incorporate a plane to act as floor, because objects will have gravity to make it lifelike.

Once one sample exercise was implemented, the overall outline was decided. The desired application needs to have three peers, as shown in **Figure 30.**

1. User interface for data input and management.
2. Gaming interface to perform exercises with Leap motion.
3. Data saving into specific folders. Analysis and management will be performed in another environment

More detailed information in Unity's objects, hierarchies and the process followed to create the platform are shown in the **developer's handbook** in **Annex D**. A brief summary is given here below, in order to understand the functionalities of each environment created:

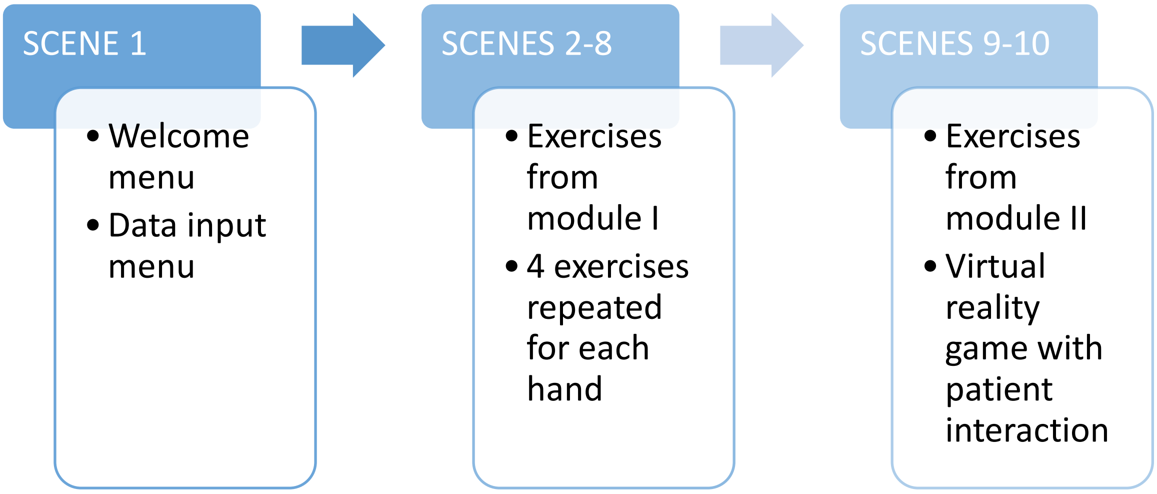


Figure 30. Outline of the different scenes of the environment.

SCENE 1: MENU

The control panel shown in **Figure 31** allows to start the game by pressing Start ("*Empezar"*) or to introduce patient's information by pressing Insert Information ("*Introducir datos"*).

Figure 31. Main menu.

The data to be introduced can be easily modified to match hospital's needs, requirements or usual way of proceeding. The data menu (see **Figure 32**) has been prototyped with two fields to be completed: name and surname of the patient and their clinical record number. By pressing Save ("*Guardar*"), a folder is created with the introduced number (not the name and surname for patient privacy reasons). A note is also created within the folder with the rest of the introduced information.

By pressing Back ("*Volver*"), we go back to the main menu.

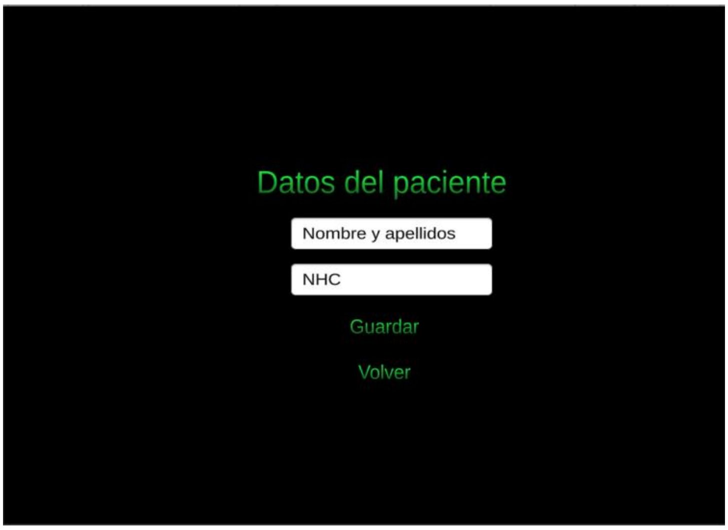


Figure 32. Patient information management menu.

SCENES 2-8: MODULE I

Once we press Start, we go to the next scene, which is the first exercise previously defined. The following exercises are part of the first module, aimed at tracking all the possible variables Leap Motion offers, in order to perform an analysis later on. They are four exercises repeated with both hands (see **Figures 33-36**).

In order to move back and forth between exercises, buttons “Back” and “Next” should be pressed. There is a brief explanatory text for each exercise, and two images exemplifying the start and end position of the hand during the task.

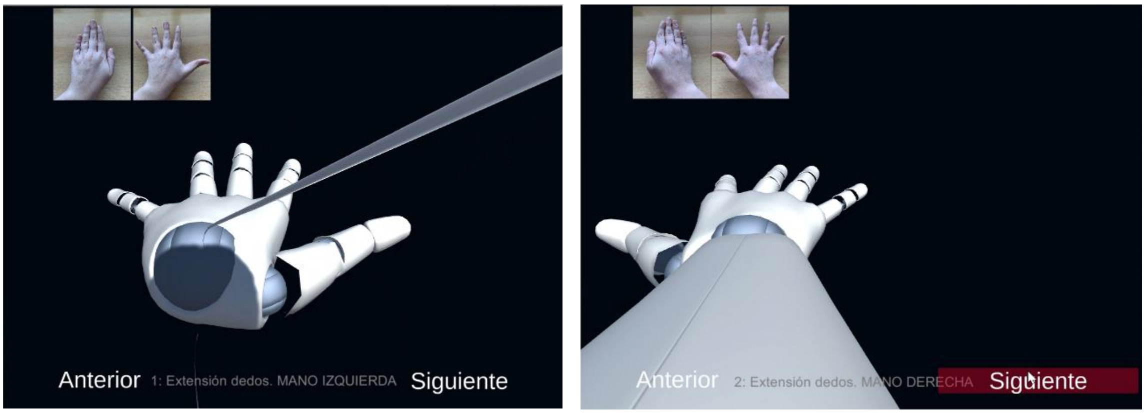


Figure 33. Exercises 1 and 2. Finger extension.

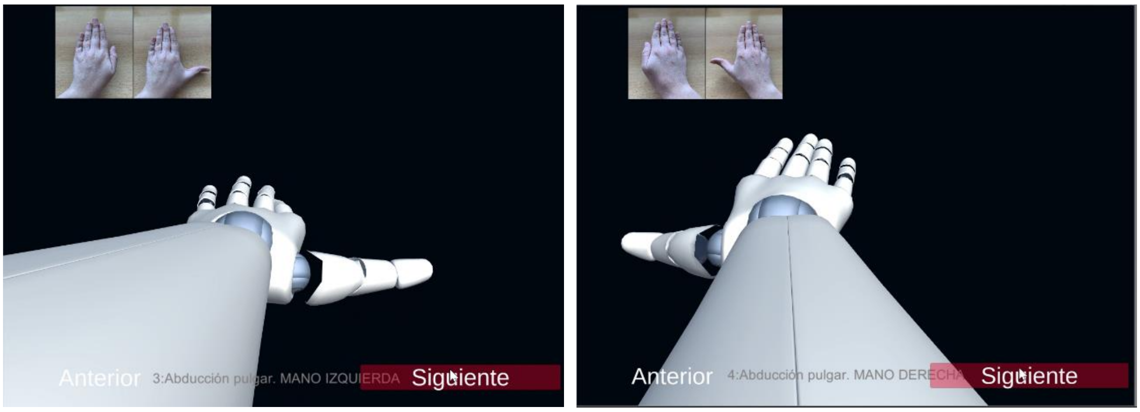


Figure 34. Exercises 3 and 4. Thumb abduction on the horizontal plane.

Figure 35. Exercises 5 and 6. Thumb abduction on the vertical plane.

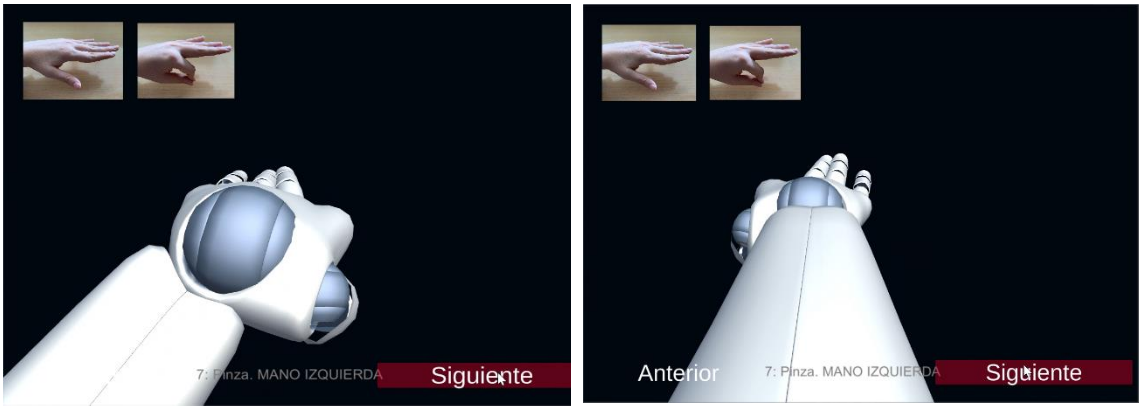


Figure 36. Exercises 7 and 8. Pinching.

SCENES 9 AND 10: MODULE II

This scene has a different approach to task-oriented exercises. It gamifies the environment to analyze patient's engagement and performance when the exercises are more interactive and dynamic.

This is a simple game where the patient will have to perform precision movements, dragging a series of cubes from one side of the environment to the corresponding platform (see **Figure 37 and 38**).

Considering Leap's limitations and the need to get used to it, the game is designed to be as easy and achievable as possible. This is why the pinching model of the hand is magnetic (i.e., the object is pinched when the hand is close enough) and the goal is achieved when the cube is within a defined range over the platform, instead of having to place it on an exact spot. When a cube reaches the platform, it is deactivated until all the cubes have been dragged and the user presses either "*Next*" or "*Finish*".

This point is important, since it was observed that first approaches to precision movements with Leap Motion are not so easy, and grasping an object with the traditional pinching method is quite challenging for people not used to the environment. Considering this module is aimed as a diagnostic method used one time on patients, we cannot develop it expecting them to learn how to play with it before using it on them.

Another element used to make it easier is a gravity script acting on the target and its corresponding cube, so if the cube falls from the user's hand, its tendency would be to approach its final destination instead of going far away.

One key point during this phase was to set the space so that the hand would appear at the optimal height and the objects (cubes and platforms) would be at a reachable distance from the hand and from each other when the exercise was done using the support system. This is important to consider, since the mobility when the hand is free over the controller is different and greater than if it must remain placed on the support.

Finally, we decided to follow the same structure as in module I and replicate the exercise so that it is done firstly with the left hand and then with the right one, to evaluate performance of the two extremities. Cubes and platforms are switched in places from one exercise to the other, to evaluate the same type of movement: from the inside to the outside (eccentric movement).

When the objective is met with the left hand (Exercise 9), the user can pass to the next and final exercise (Exercise 10) and repeat the process with the right hand until they achieve it and can finish the whole experience.

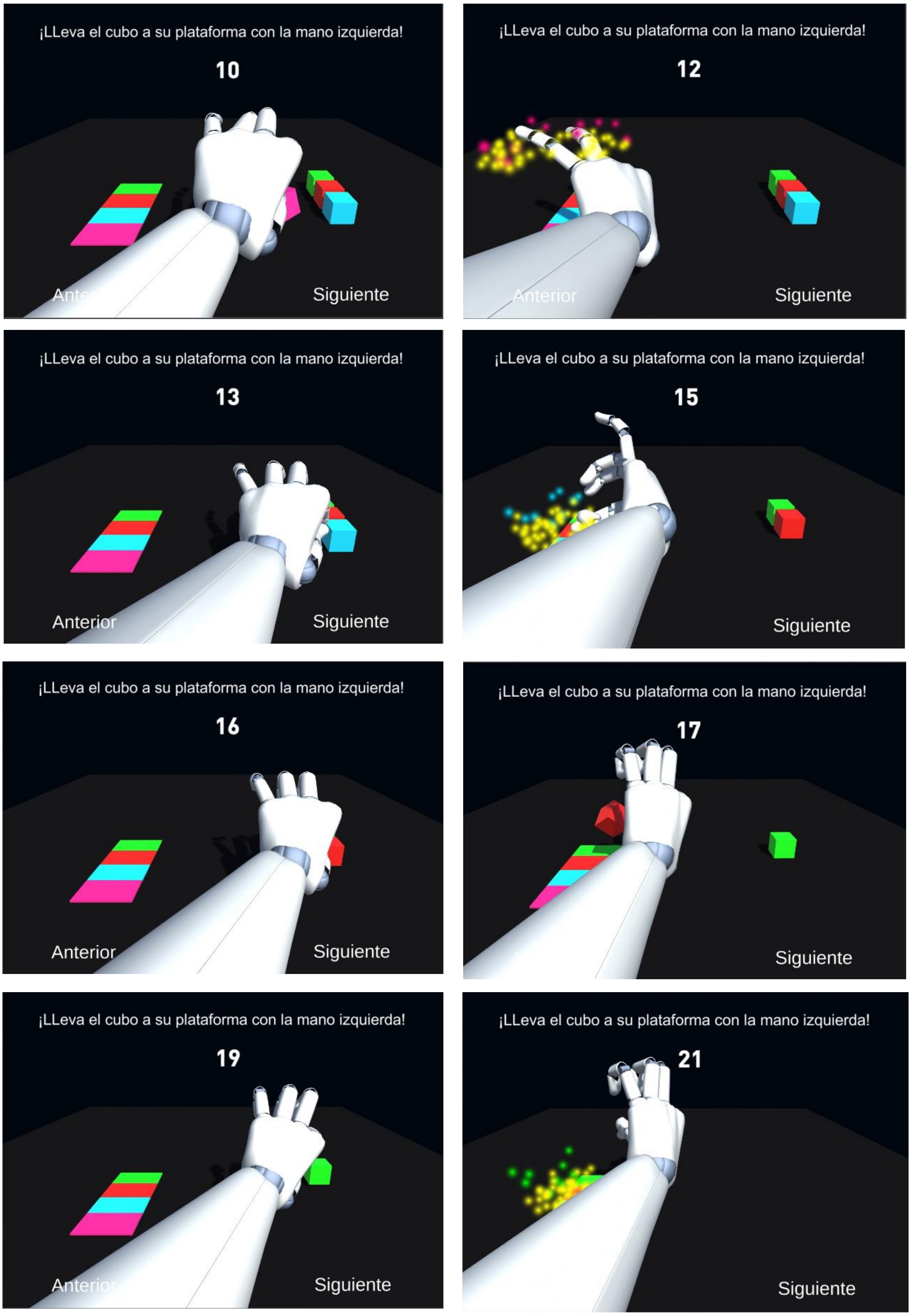


Figure 37. Exercise 9. Dragging cubes to their corresponding platform with the left hand.

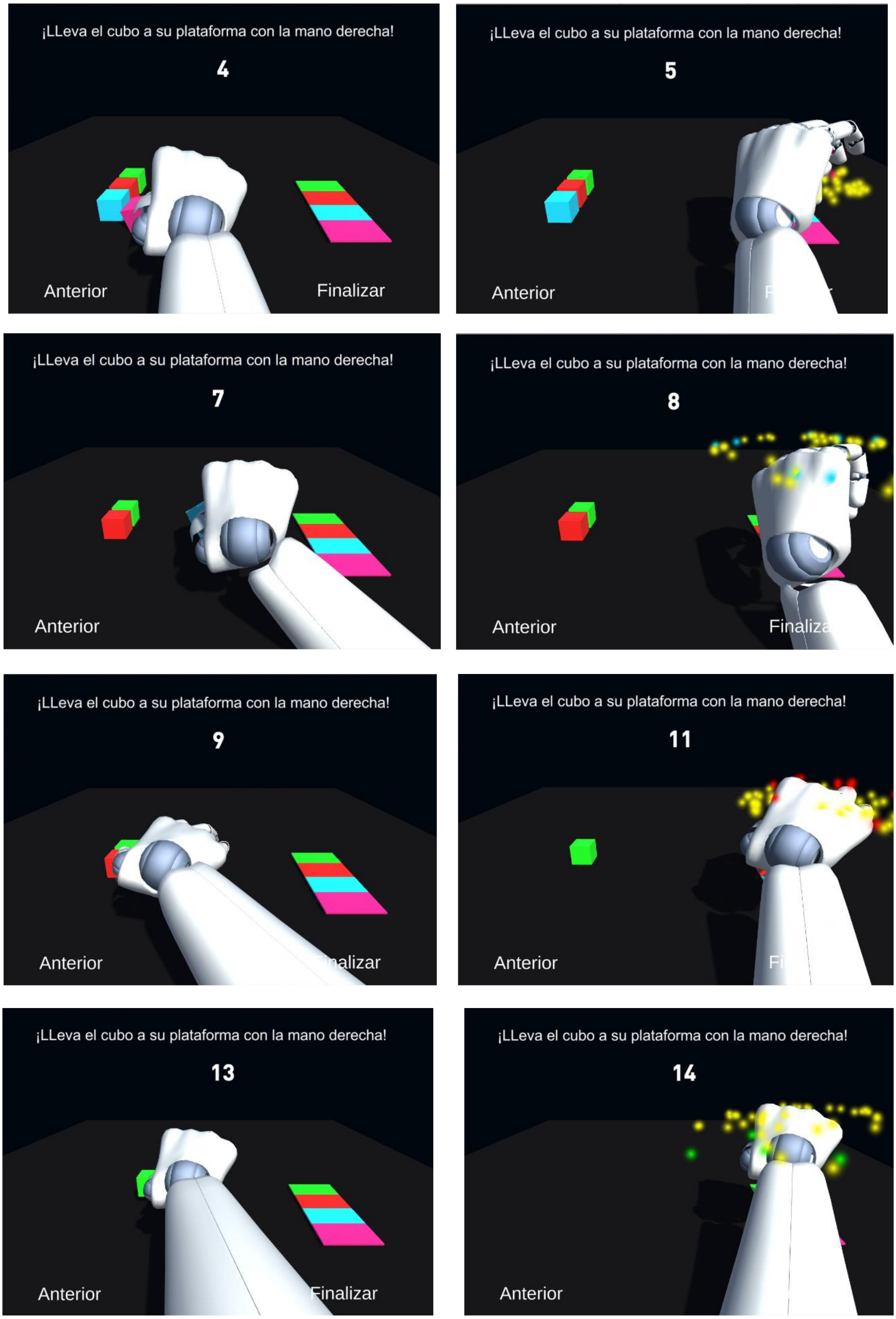


Figure 38. Exercise 10. Dragging cubes to their corresponding platform with the right hand.

3.5 Data collection

The final step of the methodology is to record patients' movement and performance during the exercise. To do so, Leap Motion is continuously tracking, selecting the most interesting variables and saving their values for them to be analyzed later. Values will update at a defined rate so that, in the end, every exercise produces an output containing all the valuable information about how the exercise was done.

The way in which the variables are collected is by creating different text files for each of the ten exercises. These files are created with the name of the exercise and each one will contain the chosen variables for every specific case. The format of these files is plain text containing the name of the variables as first line, and the value they have had all along the exercise. During the time that it takes the patient to do the exercise, the value of these variables will be updated for each frame. Using *FixedUpdate*(), we guarantee that the values are updated at a constant rate of 0.02 seconds [54].

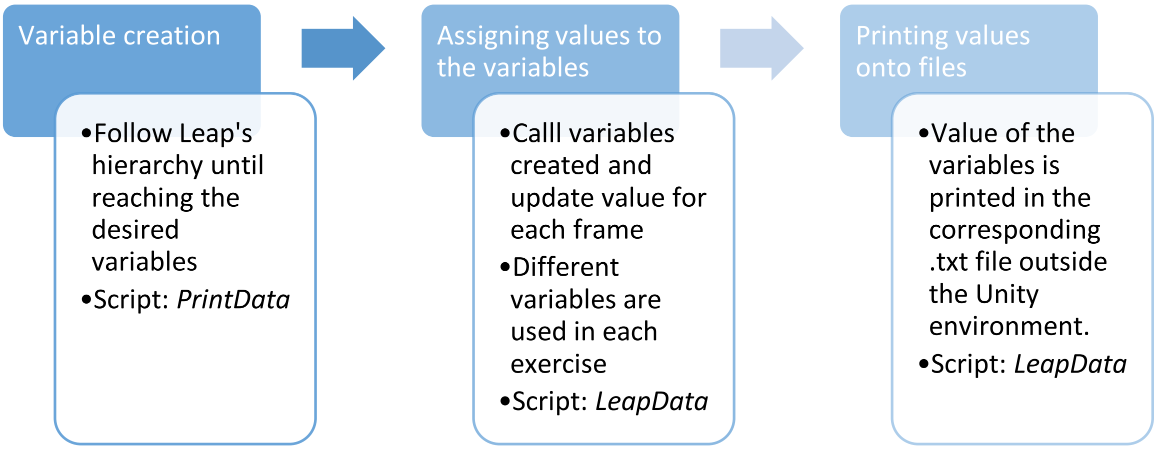


Figure 39. Outline of the different scenes of the environment.

The steps are shown in **Figure 39**.

1. Creation of the variables taking into account Leap Motion's hierarchy of objects. For example, the way the controller saves the x coordinate of the position of the fingertip of the thumb of the left hand is:

   HandList→ *HandObject* (Right or Left)→*FingerList*→*FingerObject* (Thumb, Index, Middle, Ring, Pinky) → *Property* (Tip Position)

2. Write the variables down. Depending on the exercise that is being played, different variables will be filled and printed onto a file with the name of the exercise. For example, even exercises only require the variables from the right hand, and uneven exercises those of the left hand.

This is important to know, because in case we play with our right in a left-hand exercise, no information will be printed in the file.
It is also crucial to print them with a proper structure, so that in later steps we can work with each variable separately and distinguish between frames. Therefore, the following structure was chosen:

- First line with the names of the variables. Variable name must start with capital letter
- Separator between variables or names: ";"
- Each frame will be a line, so when printing the variables, at the end of each line there must be a line break (\r\n or \n) to mark the end of a frame.

The result obtained is a set of ten files saved in the specified folder, each file with the name of the exercise and in .txt format. Within each file, the name of the variables that were saved for each exercise and the corresponding values they had during the time it took the patient to perform the exercise, separated by ";" and with a line break "/n" to separate each frame.

Variables collected

The overall variables collected are shown in **Table 3**:

Variable	Units
Tip position of a finger (x, y, z)	Millimeters
Tip speed of a finger (x, y, z)	Millimeters per second
Tip position of hand center (x, y, z)	millimeters
Tip speed of hand center (x, y, z)	Millimeters per second
Angles (Pitch, Yaw, Roll)	radians
Lifetime of hand object	microseconds
Strength	0 for an open hand. Blends to 1 when closing
Pinch	0 for an open hand. Blends to 1 when pinching

Table 3. Variables collected in the game and their corresponding units.

These variables were separated by right or left first, and for each finger secondly, and were then included in the corresponding exercises. All of them were included EXS 1,2, 7-10. However, EXS 3-6 only included those related to the thumb for the tip position and speed.

The table shown in **Annex E** provides more detail of what variables were included the different exercises.

4 Results

4.1 Analysis of results

The purpose of this chapter is to cover the last two objectives of this MSc Thesis: “Data collection on control subjects and stroke patients” and “Extracted data analysis”. The main goal is to guarantee the coherence of the data recorded during the exercises, by reconstructing it and confronting it with how the exercises were done. The expected result is to obtain a technical validation that would set the start line for the developed environment to be deployed within the hospital.

To guarantee that the extracted data was indeed what was expected, a tool was created with Matlab that takes as input the .txt created during the game with the information of the previously explained variables. The outputs of this code are two: a graphical representation and a set of three tables with the most important information extracted from the analysis.

Although the original idea was to develop this analysis tool and apply it on stroke patients from the University Hospital La Paz, this was not possible due to Covid-19 crisis [7]. Therefore, the new goal was set to validate the results obtained with the game and identify the key aspects that should be analyzed in the future. Whenever this happens, a thorough data analysis should be done to understand the behavior of patients depending on their degree of affectation, and to compare it to healthy subjects.

The following graphs and tables are not aimed at extracting conclusions about the precision or statistical behavior of these data, but to show the type of information this tool provides, and exemplify the type of analysis to do while doing a clinical study at a greater scale that includes more subjects. It will be remarked later due to its relevance, but it is important to clearly state that the following data (graphs, tables, specific values) is extracted from a single user experience that was indeed the most adequate one after a series of attempts. Therefore, the conclusions extracted along the process are not aimed at generalizing or setting a standard, but towards stablishing hypothesis and a methodology of analysis to be applied when this project continues.

4.1.1 Data preparation

The raw data is exported from Unity in the form of .txt. Unity prints decimal numbers with comma, but Matlab only reads decimals with a point “.”. If in a Spanish computer, the first step to begin the analysis is to convert Unity’s number format into Matlab’s.

The required steps are the following:

1. Modify the file created by Unity substituting the decimal separator ‘,’ with ‘.’ so that Matlab identifies numbers as double instead of char.
2. Create tables with data and variables names as shown in **Table 4**:

Left_index_x	Left_index_y	Left_index_z	Left_middle_x	Left_middle_y	Left_middle_z
mm	mm	mm	mm	mm	mm

Left_ring_x	Left_ring_y	Left_ring_z	Left_thumb_x	Left_thumb_y	Left_thumb_z
mm	mm	mm	mm	mm	mm

Left_pinky_x	Left_pinky_y	Left_pinky_z	LeftStrength	LeftPitch	LeftYaw	LeftRoll
mm	mm	mm	-	rad	rad	rad

LeftHandCenter_x	LeftHandCenter_y	LeftHandCenter_z	LeftHandSpeed_x	LeftHandSpeed_y
mm	mm	mm	mm/s	mm/s

LeftHandSpeed_z	LeftPinch	LifetimeOfLeft HandObject	Left_index_Vx	Left_index_Vy	Left_index_Vz
mm/s	-	µs	mm/s	mm/s	mm/s

Left_middLe_Vx	Left_middLe_Vy	Left_middLe_Vz	Left_ring_Vx	Left_ring_Vy	Left_ring_Vz
mm/s	mm/s	mm/s	mm/s	mm/s	mm/s

Left_thumb_Vx	Left_thumb_Vy	Left_thumb_Vz	Left_pinky_Vx	Left_pinky_Vy	Left_pinky_Vz
mm/s	mm/s	mm/s	mm/s	mm/s	mm/s

Table 4. Example of variables printed for exercise 1 and their corresponding units

4.1.2 Signal processing

There are some aspects of the different represented signals that introduce noise and are clearly outliers that do not give any relevant information. Such is the case of the following image (See **Figure 40**), where we can appreciate very high peaks and values in the beginning or end that clearly do not correspond to the movement of the user. The red and black markers correspond to the maximum and minimum speed reached, respectively. These high and low values maintained during a certain time may be produced when the game starts recording and the hand is not yet visible for the controller.

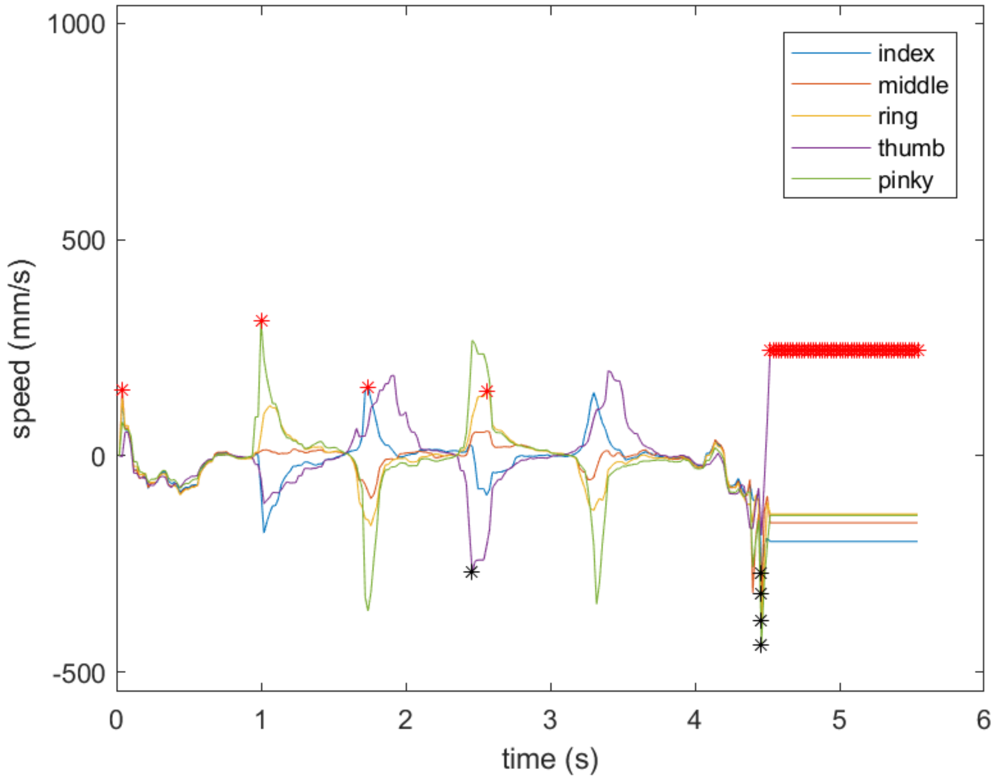


Figure 40. Unfiltered representation of speed evolution along X over time for Exercise 2

To reduce the effect of these noises (repeated values and high intensity peaks), we decided to process the image twice. Considering how little information we have about the importance of these values, specially the high intensity ones, we cannot aim at completely erasing them, in case it is proven that they are actual values coming from the patient and not the effect of noises produced by the controller. This is why a one-dimensional low order smoothing filter was applied. The filtering process is automatic regardless the input data, and it goes as follows:

1. Delete the first and last values that do not change and generate noisy straight lines. To find these lines, we defined the differential of the first line, and as long as it was zero, it was erased.
2. Apply a one-dimensional fifth order median filter to reduce the most pronounced values. In the case where these peaks are in the beginning and the end, most of the times they still represented the maximum and minimum values. However, we cannot erase them, since they may be produced by the patient when they place or retract the hand at a higher speed than when they do the exercises later.

The result of these two steps creates a much easy to interpret graphical output. The effect on the previous signal is the following, shown in **Figure 41.** The maximum and minimum speeds appear at other points and the straight lines in the end have disappeared.

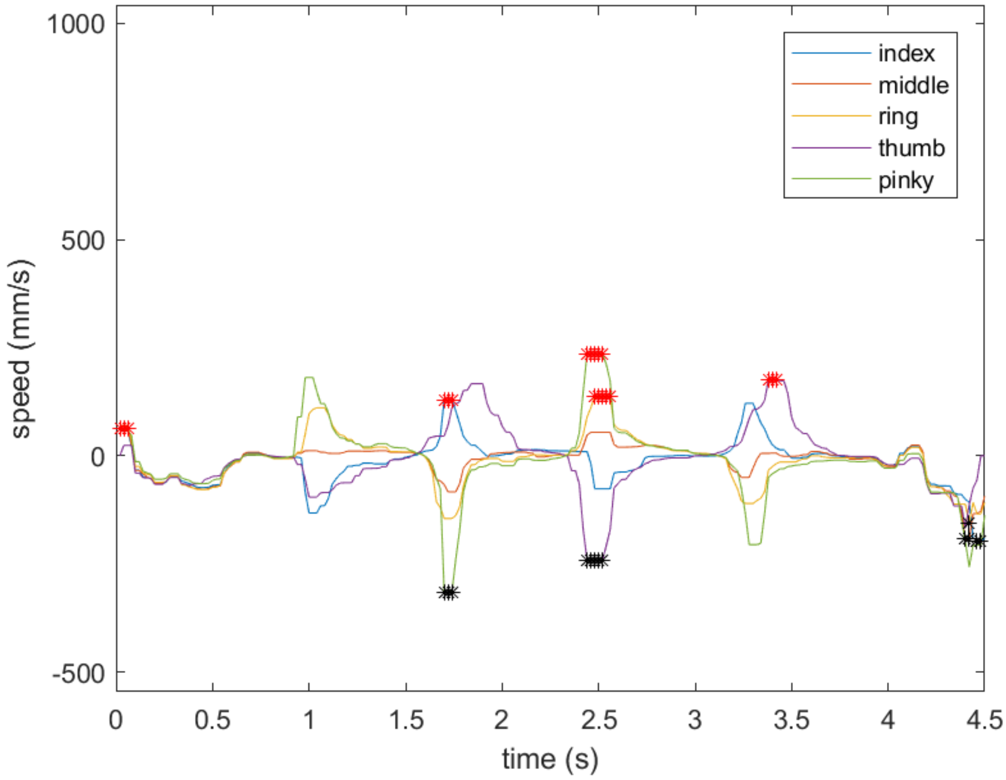


Figure 41. Filtered representation of speed evolution along X over time for Exercise 2.

4.1.3 Data feature extraction and representation

Each pair of exercises (left and right hand of each type of movement) will follow a slightly different analysis, using the variables available for each one in the created tables, and considering different approaches in terms of useful information to extract.

As previously mentioned, the output of this process is twofold: a set of tables saving what have been considered to be the most important variables, and the corresponding graphs.

These outputs are obtained automatically just by running the code. The purpose was to have an easy-to-use tool that could be used by clinicians without the need for knowing the code implementation. The detailed information on what to do to use the whole VR environment, extract data and generate results with this tool are explained in **Annex C** (user's manual).

4.1.3.1 Output 1: Tables

The most relevant information that could be extracted from the collected data has been separated into three different tables: movement, speed and angles. Not every exercise collects every variable, but all of the variables names explanations are explained in **Annex F**, along with an example of these tables for each exercise. It is not included in the body of this document due to the lack of information that a single-subject analysis could provide. The objective pursued by creating these tables is to summarize a series of defined variables that could characterize patient's movement. In a future, the virtual reality environment should be tested on more healthy subjects and patients, which will provide enough sources of information to extract conclusions.

In summary, the variables collected in the tables have to do with movement amplitude for the Movement table (maximum range of movement for each finger and the hand center, and distance between fingers); maximum and minimum speeds reached by fingers and hand center for the Speed Table; and maximum, minimum and mean angles (yaw, pitch and roll) for the Angles table.

Some of the hypothesis made that should be contrasted are:

- There is a difference between output coming from healthy patients and patients suffering from motor disorders happening after stroke
- These differences are measurable by a series of key indicators and statistical variables. For example, healthy patients will have more stable results, less difference between hands, wider range of movements, will require less time to perform the exercises and there will be less difference between both hands.
- The outcome difference is proportional to the degree of affectation of the patient.

4.1.3.2 Output 2: graphs

I. Graph preparation

Matlab adjusts the graph limits each time to the values of that certain represented variable. This is why, a function was implemented to extract the minimum and maximum values of the variables that will be plotted in the same way, and create different graph limits. These limits are different for modules I and II because speeds and ranges of movement are very different and, since they have a totally different approach, there is no need to adjust them one to the other. Moreover, exercises that only include the thumb adjust only to thumb values. In this way, the different graphs obtained will be comparable when the comparison is valuable.

Moreover, this is an automatic tool that works independently of the values of the data introduced.

II. Module I graph analysis

There are many similarities in the behavior observed for the different exercises of Module 1, which is why an altogether analysis of exercises 1-8 has been done. A visual representation of certain aspects can help to understand how this tool works and the type of parameters to seek while performing a thorough analysis.

The methodology followed to explain this section has two steps, defined to avoid unnecessary repeating that may densify this process:

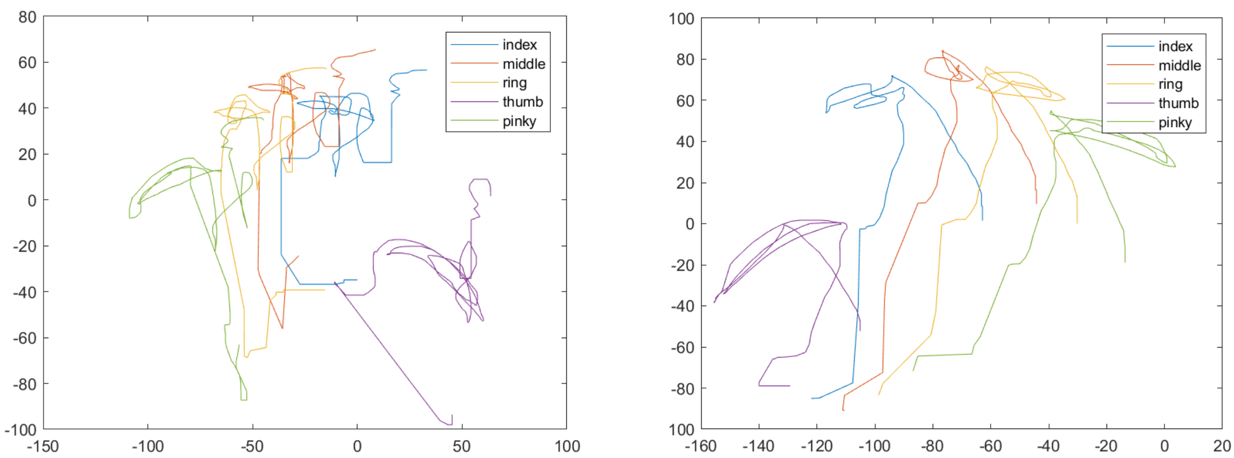
A. Common analysis.
B. Specific analyses for certain exercises.

For the common analysis, the main aspects to represent are those with the most visual information, such as finger's movement, progression of speed for each finger and hand center, distance between fingers, etc. These variables will be chosen as those that provide the most information about the performance.

The analysis of finger's movement reproduced over the plane, shows how movement of the tips is not exactly linear (see **Figures 42-45**) although the represented movement is clearly visualized. For the exercises performed on the horizontal plane (EXS 1-4, 9,10), the coordinates represented are the X and Z, whereas for those where the significant movement is vertical (EXS 5-8), the plane of projection is the YZ. The remaining coordinate is the measurement of finger stability.

This representation can serve as a first discrimination of whether the information collected is more or less accurate having seen the patient's performance, because if the movement is not well represented, all of the posterior information must be affected as well.

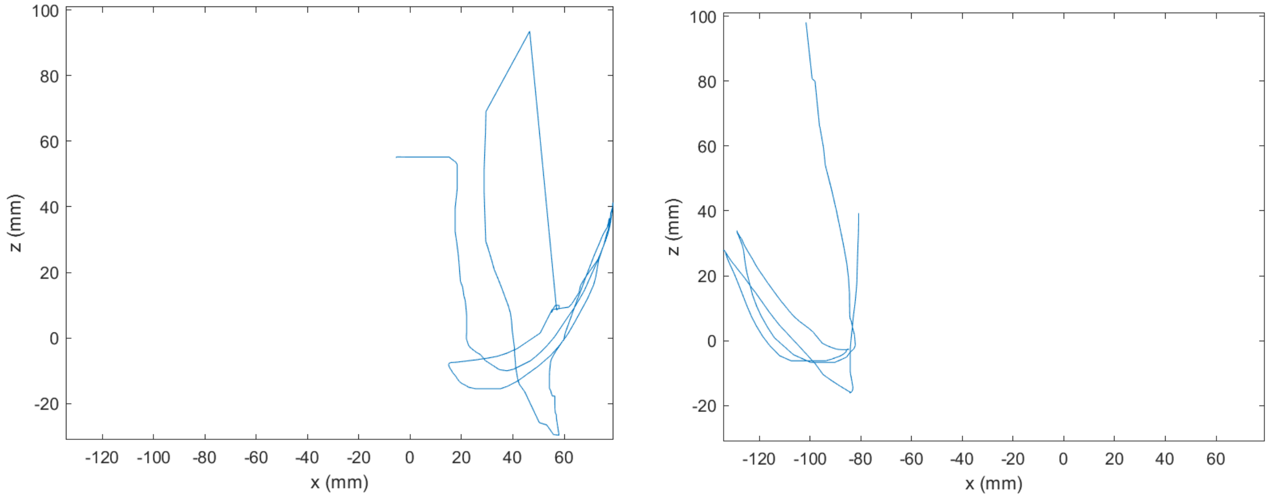
For exercises 1 and 2, the five fingers are represented in different colors (purple for the thumb, blue for the index, orange for the middle, yellow for the ring and green for pinky), as shown in **Figure 42**. The initial straight lines that increase in z correspond to the colocation of the hand in the initial moments, and the lines at the top that over cross represent the trajectory of the fingers' tips. We observe a greater range of movement for the right hand than for the left hand, as well as a more stable movement for the right hand. This stability can be seen with a cleaner representation, with less tremor and a clearer vision of how the movement was performed.



(a) **(b)**

Figure 42. Exercises 1 and 2. Finger extension for a) left and b) right hand. Movement on XZ plane

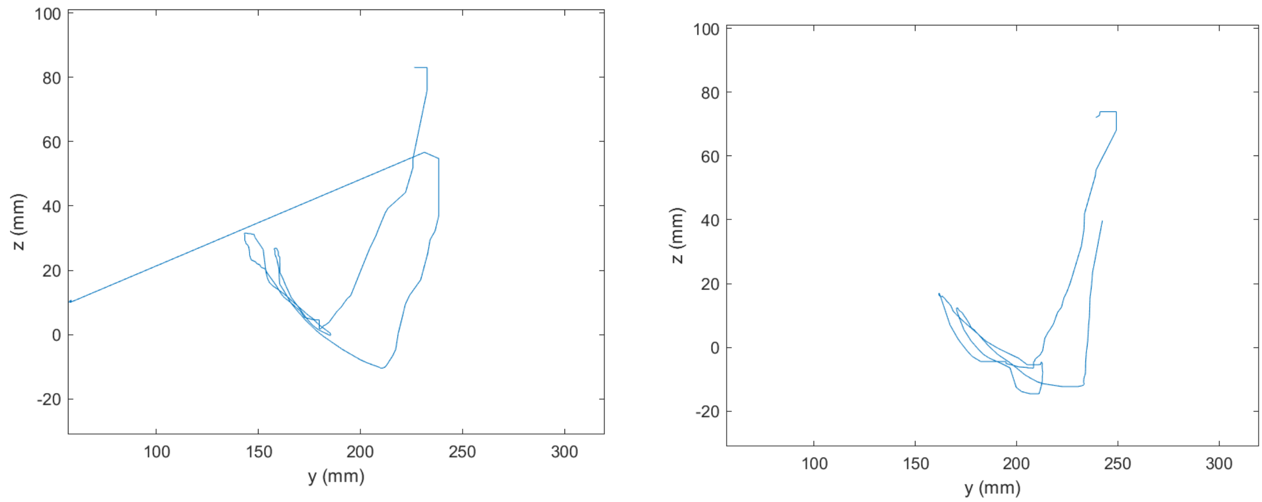
In the case of exercises 3 and 4, only the thumb movement is represented. We can appreciate how its movement is similar to the one of the thumb in **Figure 42**, since the exercise is the same but only implicating the thumb. In **Figure 43**, we see how both trajectories are quite similar, with almost the same amplitude in x and z, which could be interpreted as equally functioning thumbs.



(a) **(b)**

Figure 43. Exercises 3 and 4. Thumb abduction on the horizontal plane for a) left and b) right thumb. Movement on XZ plane.

For exercises 5 and 6, where the thumb movement occurs in the vertical plane, as depicted in **Figure 44**, we see that the left thumb's trajectory overlaps more in the back-and-forth movement, whereas the right thumb deviates more. We see a similar behavior in terms of amplitude.



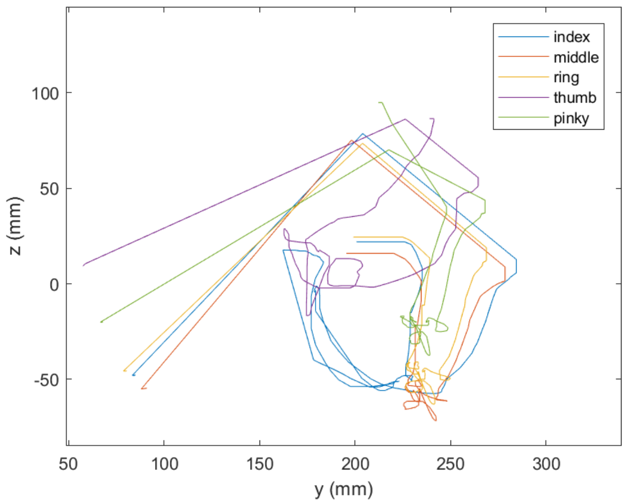
(a) **(b)**

Figure 44. Exercises 5 and 6. Thumb abduction on the vertical plane for a) left and b) right thumb. Movement on ZY plane.

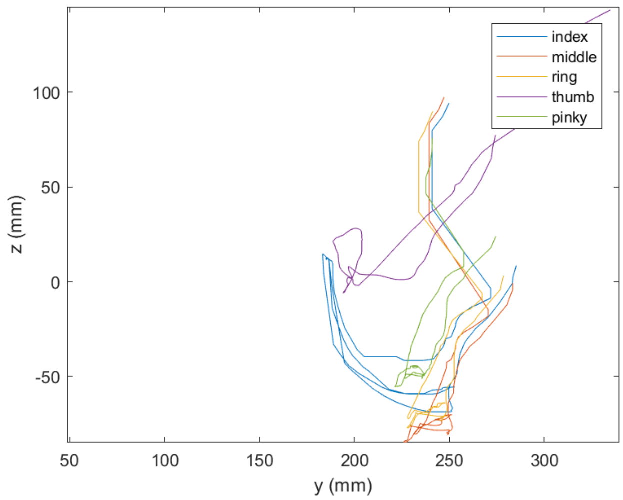
Exercises 7 and 8 representation in the vertical plane shows in blue the index finger and in purple the thumb (see **Figure 45**). In both cases, we see how they encounter, although for the left hand their positions overlap more, and for the right hand they do not reach the same coordinates. This may be an imprecision of Leap Motion, since the exercise was performed pressing the tips together twice.

To continue, we can observe how it is the index the finger that moves the most along the blue curve, starting around (250,-50) and encountering the thumb at (190, 10), whereas the thumb remains around the purple nod, around (200, 0).

Moreover, we see how, in both cases, we get an initial straight line corresponding to the colocation of the hand, and a blur of lines at the end of the other fingers, since they move along while the subject pinches. We can see how the right hand provides a steadier reconstruction of movement, with lines straighter and more overlapped. This could be a result of a firmer movement with the right hand, which in the experiment case is the dominant one. Considering how pinching is a movement usually done with the dominant hand, used to grab objects and do precision movements, it seems reasonable that the right-hand pinching would be cleaner and more precise.



(a)



(b)

Figure 45. Exercises 7 and 8. Pinching for a) left and b) right hand. Movement on ZY plane

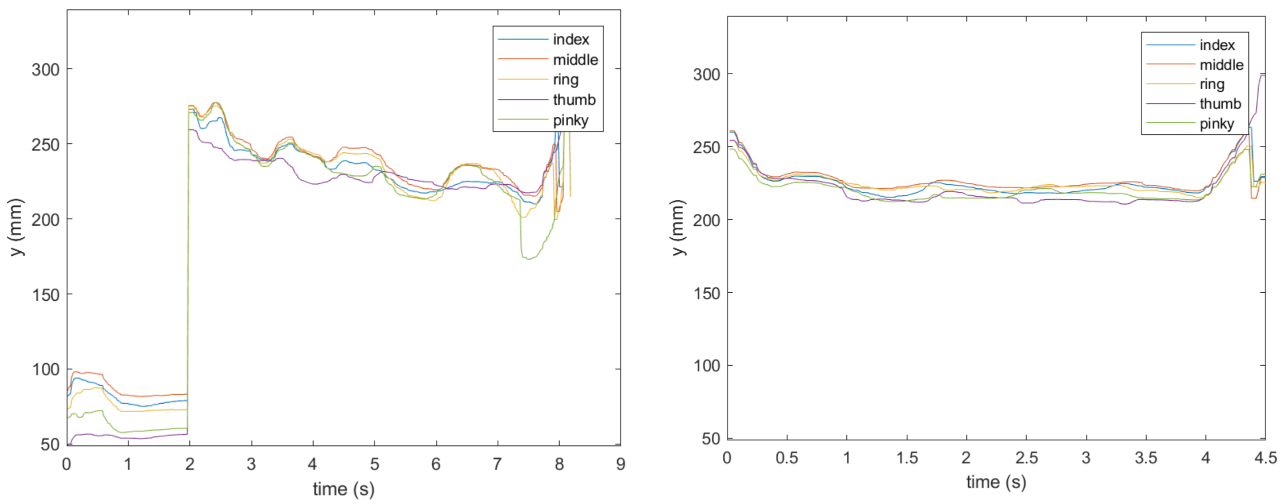
The following represented variables are the trajectory of fingers over time. For both fingers and hand center stability, a difference is observed between the left and the right hand. This difference can be directly observed while performing the exercise (appreciated in **Figures 46-57**). This may mean that the difference between hands in this variable, or maybe even differences within the studied population, do not have relevance. This would be because everyone performs the exercise differently even while healthy, so differences related to stroke and motor impairment may not be differentiable. This can only be confirmed performing the tests on a wide population.

Besides the deviation peaks produced because of the fingers' movement, we can observe a general tendency where the deviation increases slightly over time. This could be related to the fatigue of the hand having to be held over the controller.

For exercises 1 and 2, represented in **Figure 46**, we have the trajectory of all fingers in the vertical direction over time (blue for index, orange for middle, yellow for ring, purple for thumb and green for pinky). The initial step observed in the left hand may be produced because of an initial detection of the hand when it is not yet properly positioned. Considering this, the beginning time would be 2 seconds, this making the movement of the left hand to last 6 seconds and the one of the right hand to last 4.5 seconds. This is a significant difference that could imply a greater easiness to perform the exercise with the dominant hand.

A very important observation extracted from **Figure 46**, is the steadiness and straightens of the curve. We see four important peaks for the left hand, corresponding to the two open-and-close movements. This adds up to a more instable curve, whereas for the right hand, there is only one significant drop in the beginning, that could relate to the initial collocation of the hand. This continues the hypothesis of a better performance with the dominant hand, but it would also be important to note that, while developing the game, all tests were made with the right hand, so there could be a learning rate affecting this better result.

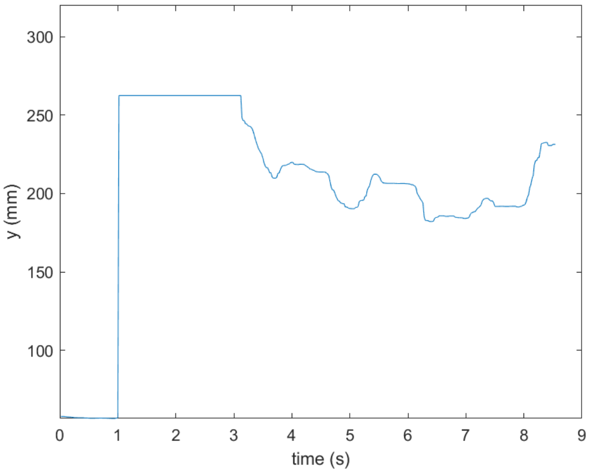
In terms of stability in the y-direction, on the left hand it is the pinky (see green line) that deviates most, but this is logical considering that its movement from closed hand to open hand includes a vertical decline. The right hand does not present great differences neither between fingers nor over time. We see a greater progressive drop in the y-direction for the left hand during the exercise, that goes from around 260-270 mm, to almost 200, confronted to the right hand curve, that is almost straight for each finger.

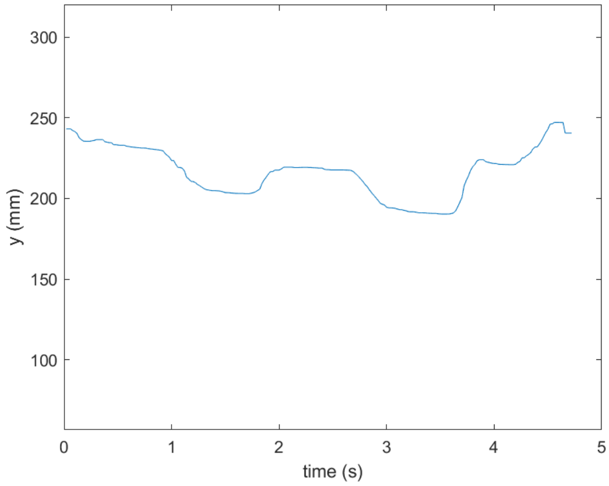


(a) **(b)**

Figure 46. Exercises 1 and 2. Finger extension for the a) left and b) right hand. Fingers deviation in the y-direction over time.

For exercises 3 and 4, similar observations could be extracted from **Figure 47**. The left hand presents more pronounced peaks than the right one, and it takes 20% more time to perform the exercise. Both curves are similar to the ones of the thumb seen in purple in **Figure 46,** although they are both sharper than for the previous exercise. This could be because the movement of abducting the thumb alone is less natural than a complete opening of the hand.

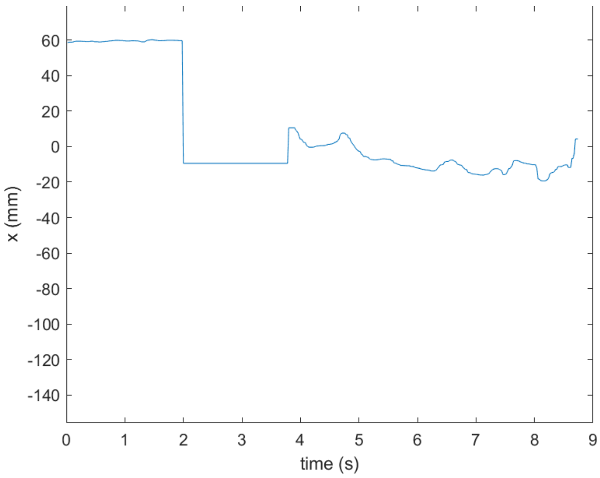


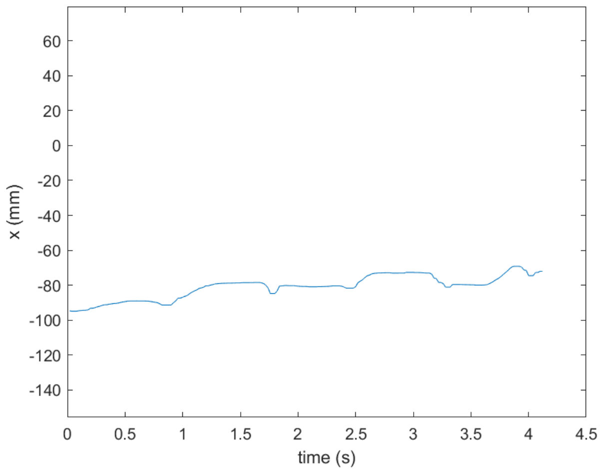


(a) **(b)**

Figure 47. Exercises 3 and 4. Thumb abduction on the horizontal plane for the a) left and b) right thumb. Thumb deviation in the y-direction over time.

In exercises 5 and 6, represented in **Figure 48**, the deviation of fingers is measured along x-direction, since the movement occurs in the vertical plane. We see that the thumb is more stable on this direction than on the previous one, with a difference of 20 mm of deviation in the x direction, against a deviation of around 50 mm in the y-direction.

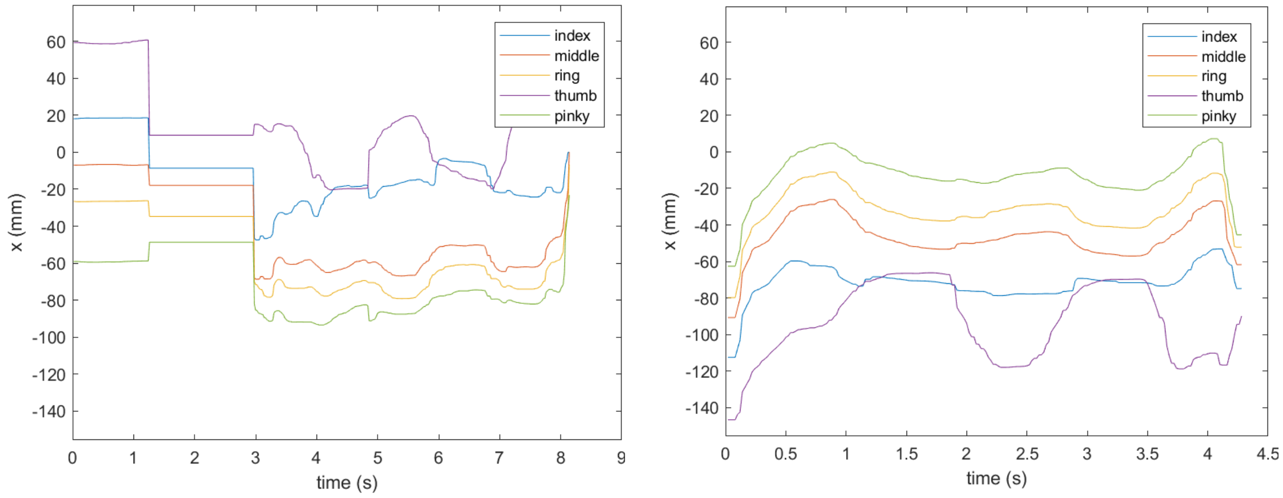




(a) **(b)**

Figure 48. Exercises 5 and 6. Thumb abduction on the vertical plane for the a) left and b) right hand. Thumb deviation in the x-direction over time.

Finally, for exercises 7 and 8 we depicted the x-deviation of all fingers, since the pinching movement happens in the vertical plane as well. In **Figure 49**, the inversion of the finger's curves from one hand to the other responds to the location along x, since the pinky of the left hand is the furthest from the pinky of the right hand. We can see two pronounced peaks for the thumb (purple line), whereas the index, which is the other finger involved in pinching, does not move that much. This means that the finger that has the most displacement in the pinching movement is the thumb, which confirms that having exercises to evaluate its functionality exclusively is important. Once again, we see sharper peaks for the left hand than for the right one, which means a more stable movement for the right hand.



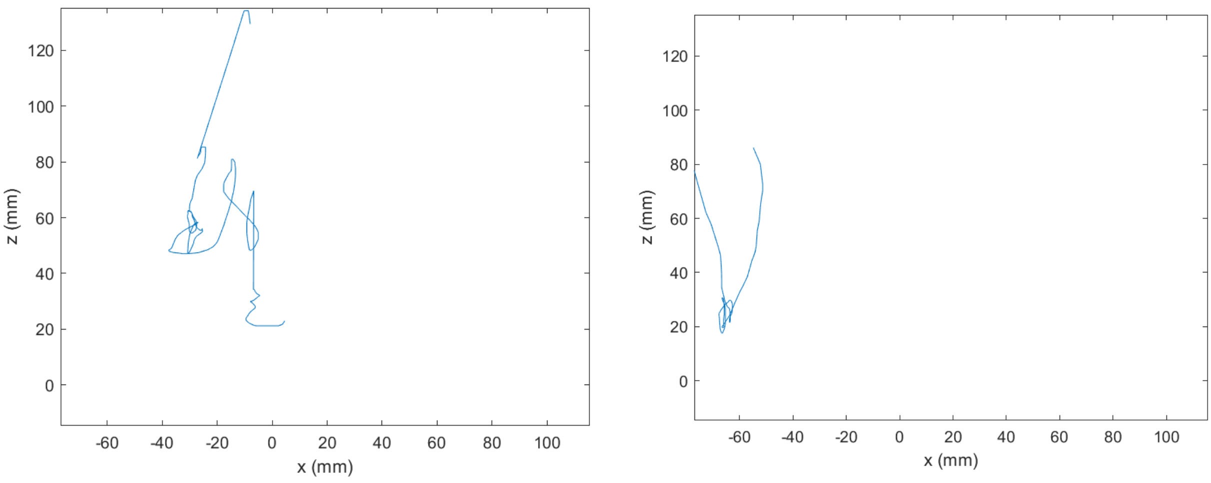
(a) **(b)**

Figure 49. Exercises 7 and 8. Pinching for the a) left and b) right hand. Fingers deviation in the x-direction over time.

For the hand center analysis, the movement plane is always the horizontal one, since this is the position in which the hand should remain for all the exercises. Therefore, the stability is measured along the y-direction (see **Figures 50-53**).

Firstly, we decided to depict the movement of the hand center on the XZ plane. It is important to see that the x coordinate of the left hand is going to tend to be around more negative values than the right one, whereas they should be around the same point in z.

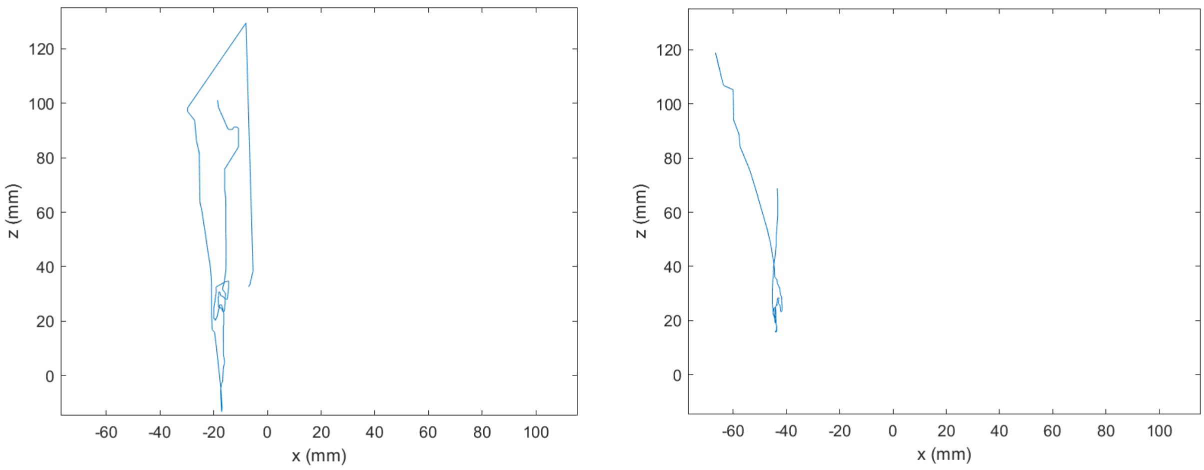
In exercises 1 and 2, represented in **Figure 50**, we can appreciate a great difference between the left and the right hand. For the left hand, it clearly moves during the exercise, whereas in the right hand we see two straight lines corresponding to the placement and retirement of the hand, and a small nod corresponding to the point around which the hand moves during the exercise.



(a) **(b)**

Figure 50. Exercises 1 and 2. Finger extension for the (a) left and (b) right hand. Movement of hand center on the XZ plane.

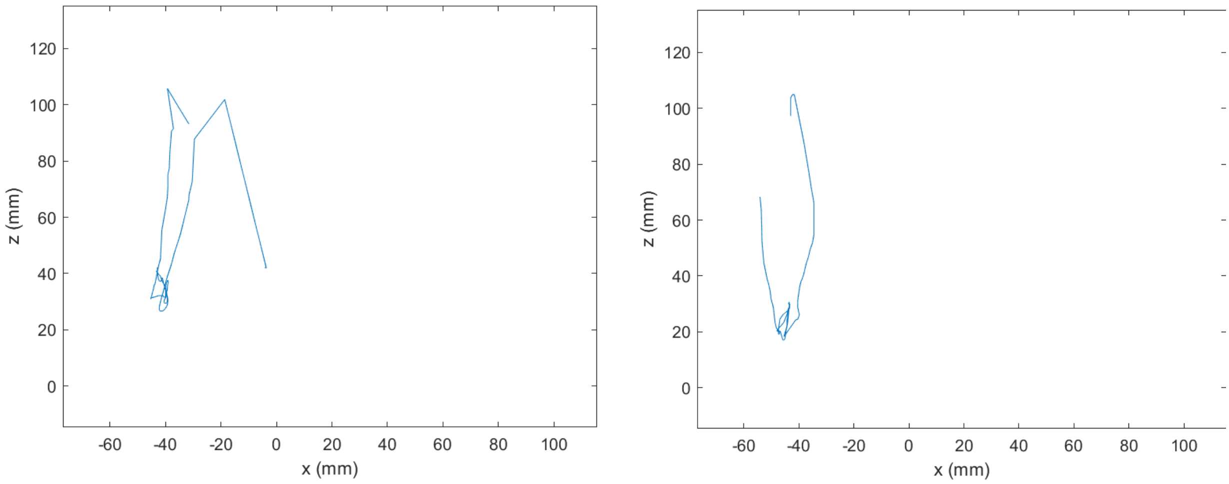
In **Figure 51**, we can observe a similar behaviour for exercises 3 and 4, with a more restricted movement of the right hand, and with the central point being around the same z coordinate. In particular, we see a great peak in the z direction, that indicates a deviation while doing the exercise in that direction that does not happen for the right hand.



(a) **(b)**

Figure 51. Exercises 3 and 4. Thumb abduction on the horizontal plane for the (a) left hand and (b) right hand. Movement of hand center on the XZ plane.

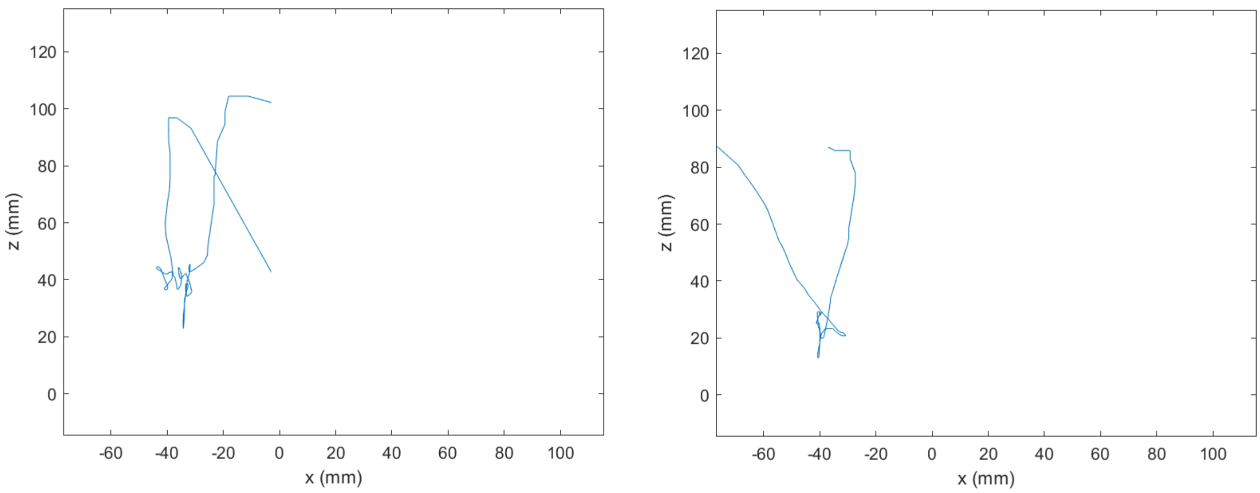
For exercises 5 and 6, shown in **Figure 52**, similar observations can be done, although there is a more similar behavior between the two hands, and the central point seems to be kept for both cases.



(a) (b)

Figure 52. Exercises 5 and 6. Thumb abduction on the vertical plane for the (a) left and (b) right hand. Movement of hand center on the XZ plane.

Finally, exercises 7 and 8 present a similar graphical representation of the hand center over the XZ plane (see **Figure 53**), with straight lines marking the entrance and exit of the hand in the field of view, and a nod representing the central point around which the hand stays during the exercise.



(a) (b)

Figure 53. Exercises 7 and 8. Pinching for the (a) left and (b) right hand. Movement of hand center on the XZ plane.

Secondly, we decided to represent the hand center's position evolution over time in the x and y direction. For a better understanding and to ease reading, we have decided to place the x representation and y representation together for each pair of exercises, so the following figures include 4 graphs at a time instead of two.

We can see that the hand center is less sensible to the movements produced by the fingers than the fingers themselves, seeing fewer peaks and a more stable curve than for the fingers' deviation (shown in **Figures 46-49**). This fact could be interesting while determining which is the best way to measure hand's stability, if fingers or hand centers' deviation.

In general terms, this curve's evolution presents a slight and progressive descend over time, so this curve's slope could provide information about the effects of fatigue while performing the exercises.

In exercises 1 and 2, shown in **Figure 54**, we can see softer curves both the x and y direction for the right hand. As for the previous exercises, the initial and final pronounced slopes have to do with the colocation and extraction of the hand on the correct position. In terms of duration, considering that left hand begins the movement at 2 seconds, we see how it takes 7 seconds for the left hand to do the open-close movement, whereas the right hand takes only 4.5 seconds.

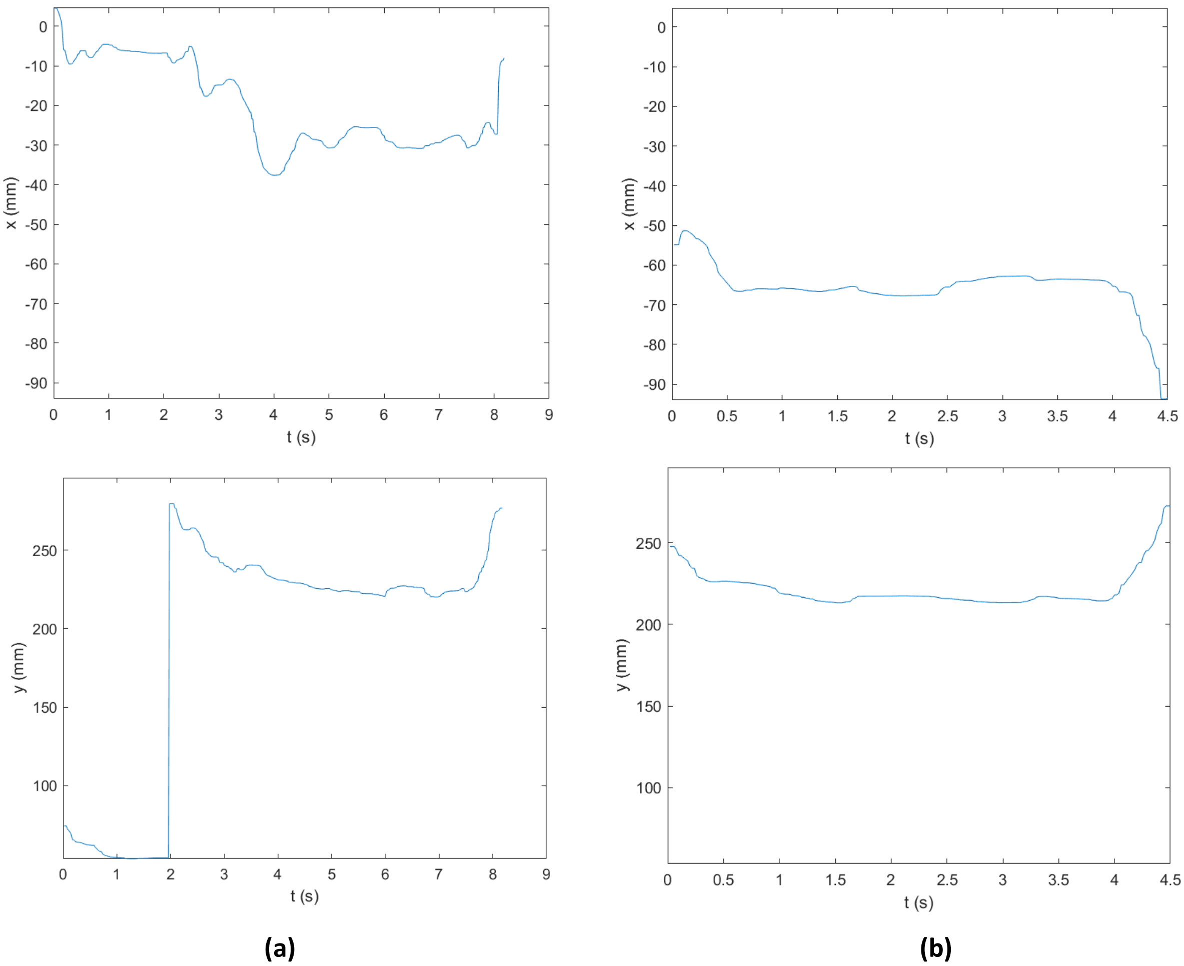


Figure 54. Exercises 1 and 2. Finger extension for the (a) left and (b) right hand. Deviation in the x (top) and y (bottom) directions.

Similar observations are done for exercises 3 and 4 (see **Figure 55**), where the initial and final slopes correspond to the arrangement of hands. The right hand achieves an almost straight line, with practically no deviation in the x or y directions, but the left hand present some peaks that could correspond to an inner tremor or to the instability produced during the abduction and adduction of the thumb.

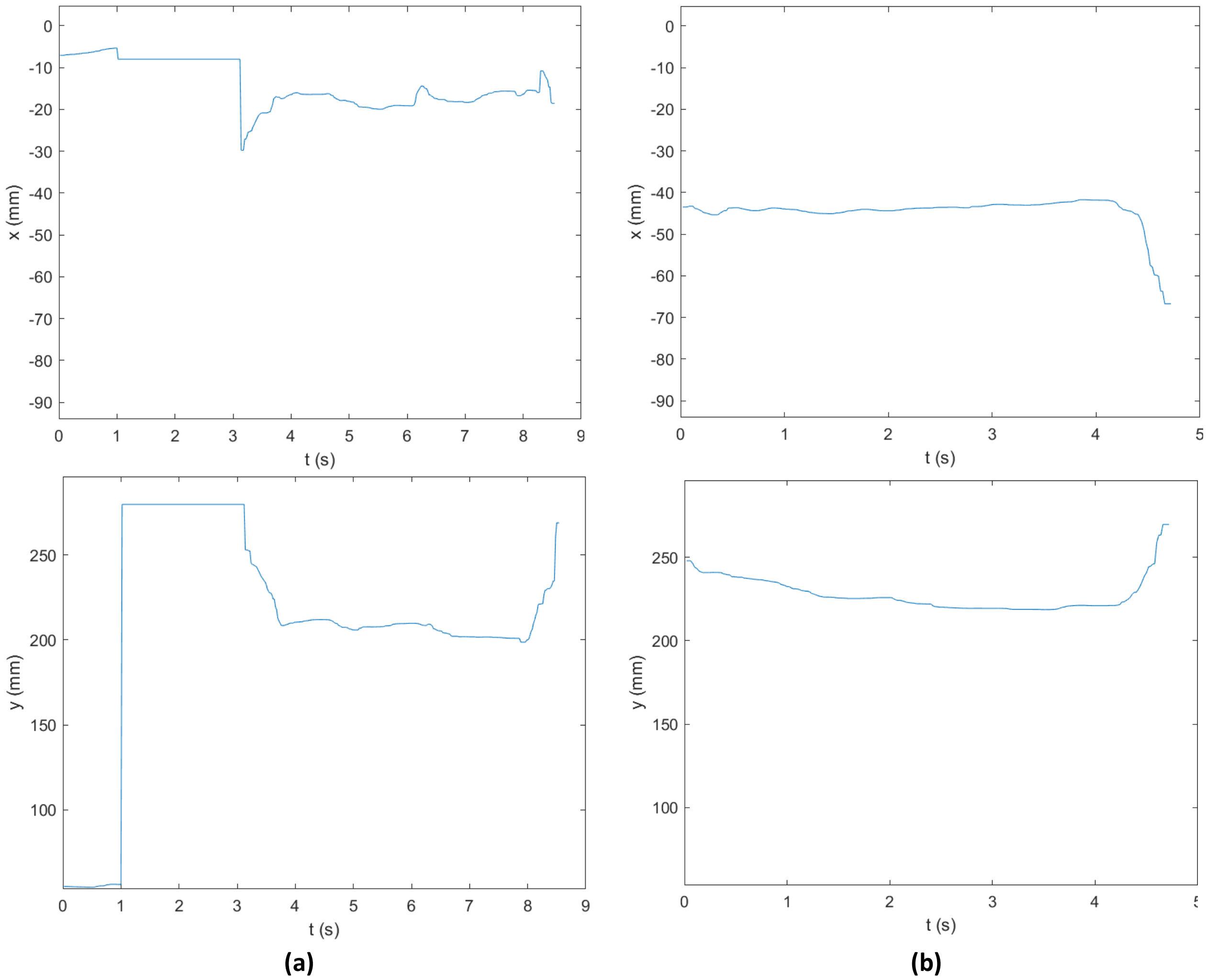
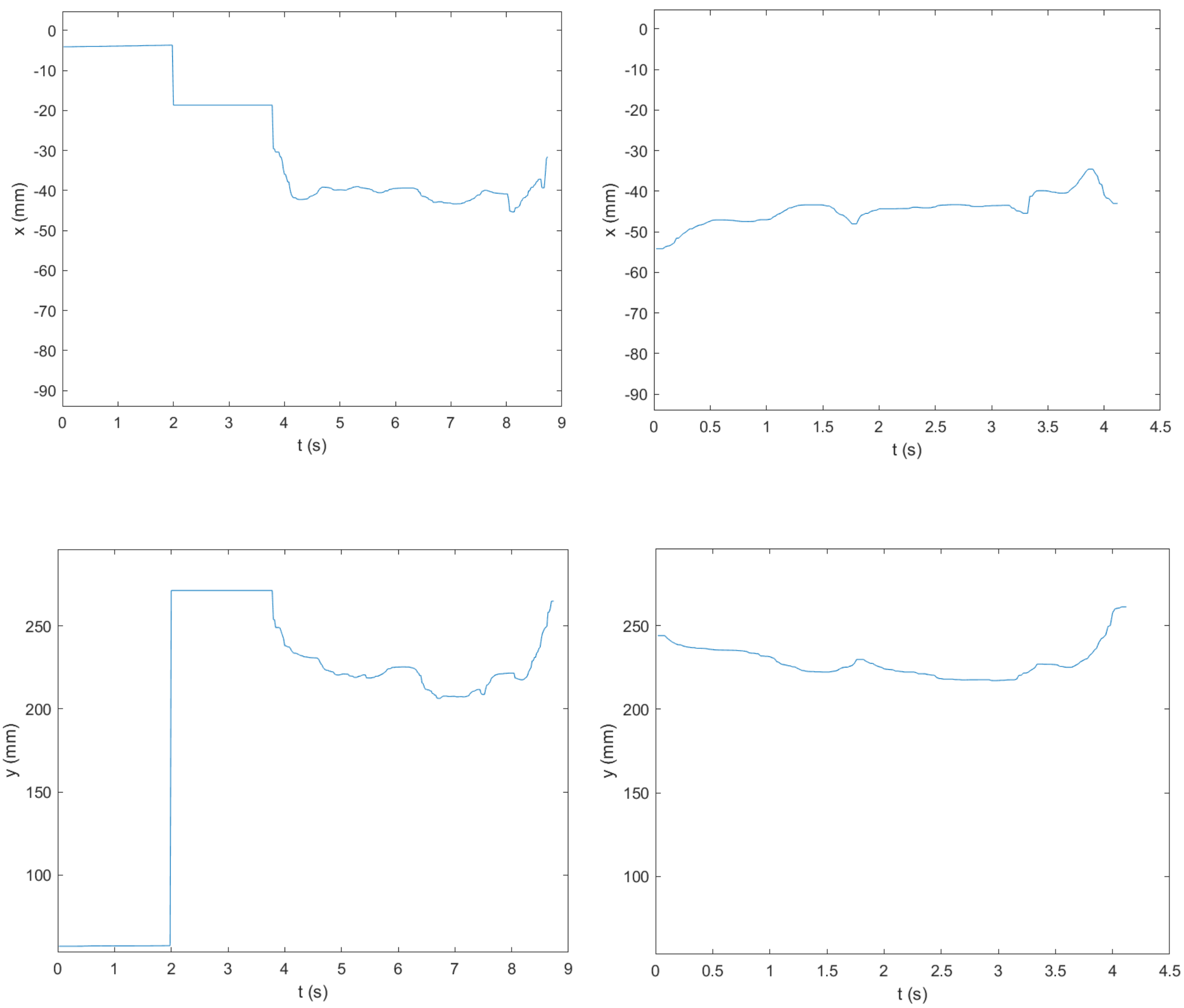


Figure 55. Exercises 3 and 4. Thumb abduction on the horizontal plane for the (a) left hand and (b) right hand. Deviation in the x (top) and y (bottom) directions.

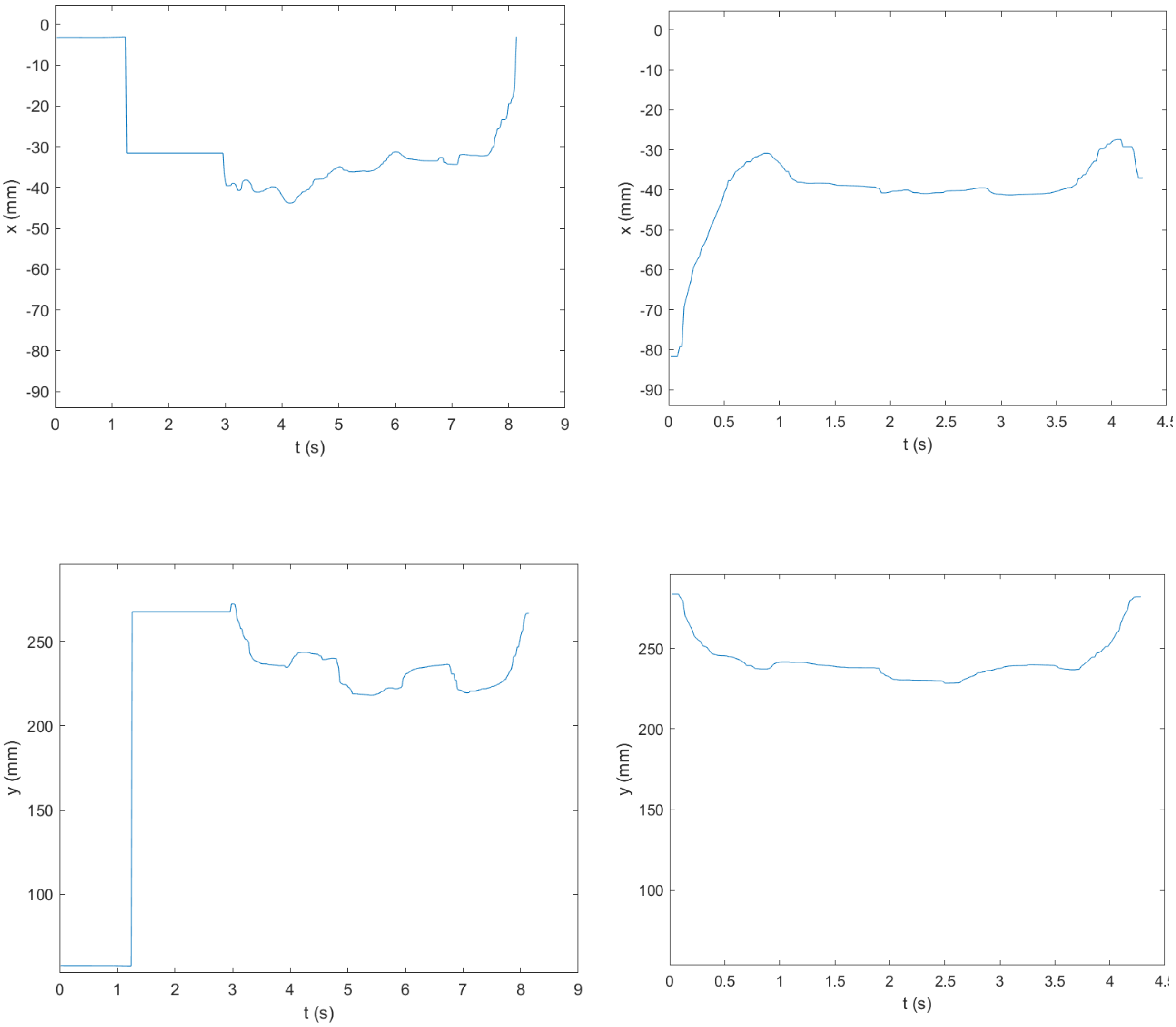
Identical behavior is seen in **Figure 56** for exercises 5 and 6, with slightly sharper peaks that could correspond to a less intuitive movement.



(a) **(b)**

Figure 56. Exercises 5 and 6. Thumb abduction on the vertical plane for the (a) left and (b) right hand. Deviation in the x (top) and y (bottom) directions.

Finally, in **Figure 57**, we can see that the difference of stability between the left and the right hand is greater than for the previous exercises. For the right hand, we see a very steady line, whereas in the left hand we see to pronounced peaks in the y direction corresponding to the moments of pinching, and a sharp curve in the x direction. As previously explained, considering that pinching is a precision movement done with the dominant hand, it would be normal to obtain a much more stable result with the right hand.



(a) **(b)**

Figure 57. Exercises 7 and 8. Pinching for the (a) left and (b) right hand. Deviation in the x (top) and y (bottom) directions.

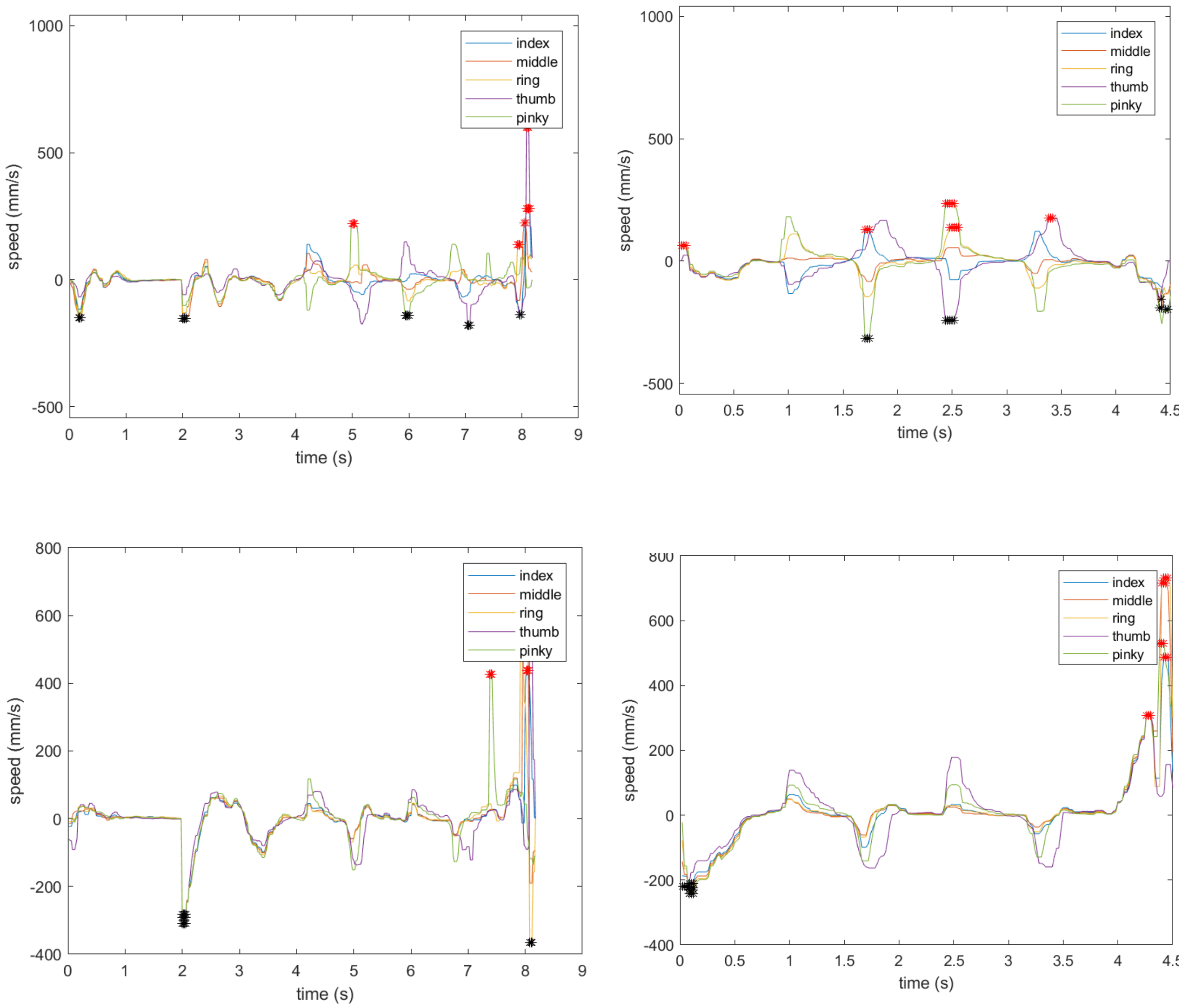
The graphical representation of speed evolution was a little different for each exercise (See **Figures 58-61**). Exercise's 1,2, 7 and 8 separate the representation of speed in the x and z direction because they analyze every finger, and representing them altoghether makes the image messy. However, because exercises 3-6 only analyze thumb's behavior, speeds along x,y and z where represented on the same graph.

We can observe how the peaks, either negative or positive and regardless of the direction, correspond with the moment in time where the movement is being produced (fingers extension, thumb abduction, pinching…). Pinky, ring and middle fingers have speeds in the same sense, whereas thumb and index move in the opposed sense. The more eccentric the finger (pinky and thumb), the greater the speed. Peak values are similar for both hands, although the right pinky reaches greater speed.

In **Figure 58**, we can see the speed evolution over time for exercises 1 and 2. In red, we see the marker indicating the maximum speed reached by each finger, whereas the black marker indicates the minimum speed. We can see how most of these markers appear at the beginning or end of the exercise, this indicating that the maximum speed occurs while introducing or extracting the hands from the field of view. When this does not happen, the highest values, either negative or positive, are distributed randomly along the exercise.

In terms of speed in x or in z, we appreciate clearer and greater peaks for the x direction (top images) than for the z direction (bottom images), since the majority of the amplitude change happens along x direction for the open-close movement. In the x directions, the maximum speeds during the exercise – excluding the peaks in the beginning and end- are around 250 mm/s, whereas in the z direction they do not reach 200 mm/s.

Finally, if we analyze each finger individually, we observe how the middle finger has the lowest speed, with little variation (orange line), which is coherent with its behavior during the exercise, where the middle finger remains practically still. Pinky (green line) and thumb (purple line) reach the highest speeds, with slightly greater values for the pinky. This is also coherent with the fact that these two fingers are the ones that displace the most from its starting point.



(a) **(b)**

Figure 58. Exercises 1 and 2. Finger extension for (a) left and (b) right hand. Speed evolution in the x (top) and z (bottom) directions.

In **Figure 59**, we see the speed evolution along the three directions for thumb abduction, with greater peaks for the left hand, but clearer differentiation of such peaks and less noise for the right hand. This could indicate a similar perfomance by the two hands, but with greater stability of the dominant hand, (i.e., the right one).

In **Figure 59 left**, we appreciate a singularity of a non-representative part of the evolution with black markers for Vx because it is the lowest speed of all the exercise, but that appears at different levels for the other two directions. These abnormalities appear to be a moment where the controller stops updating the values or loses the hand, and sets them for a time, in this case 2 seconds. Considering that we have already erased the initial and final values that do not give information and appeared as a straight line as well, and that these tests were made with a healthy and experienced subject, we could hypothesize that there is noise introduced by the controller when it is unable to detect the hand.

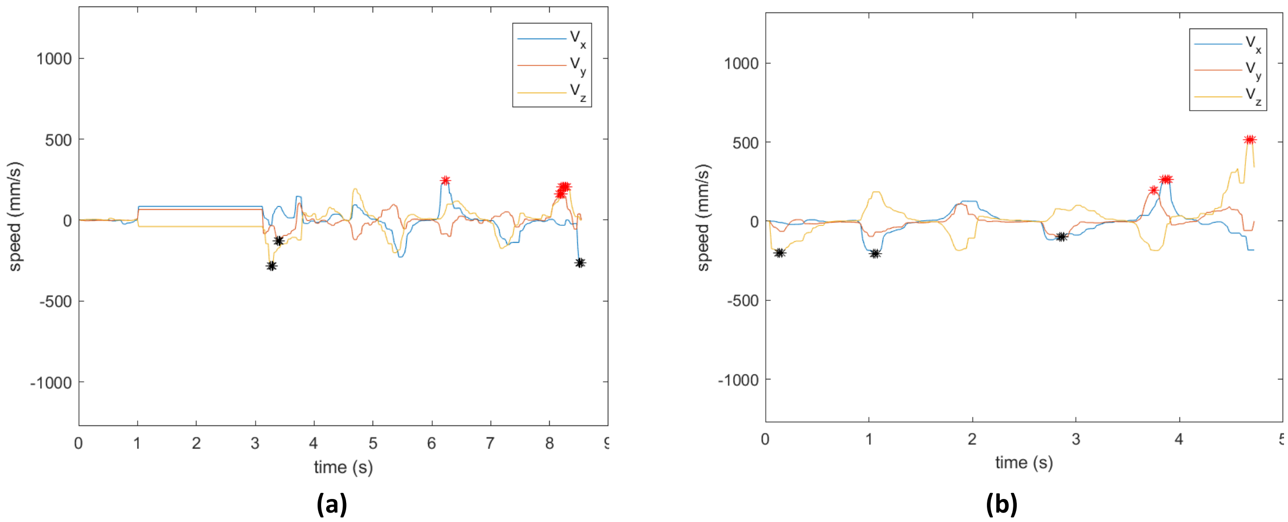


Figure 59. Exercises 3 and 4. Thumb abduction on the horizontal plane for (a) left and (b) right thumb. Speed of thumb in the x, y and z directions evolution over time.

The observations that can be done for **Figure 60**, representing exercises 5 and 6, are practically identical to the previous exercise, with clearer curves for the right hand and a singularity occurring during 2 seconds for the left hand.

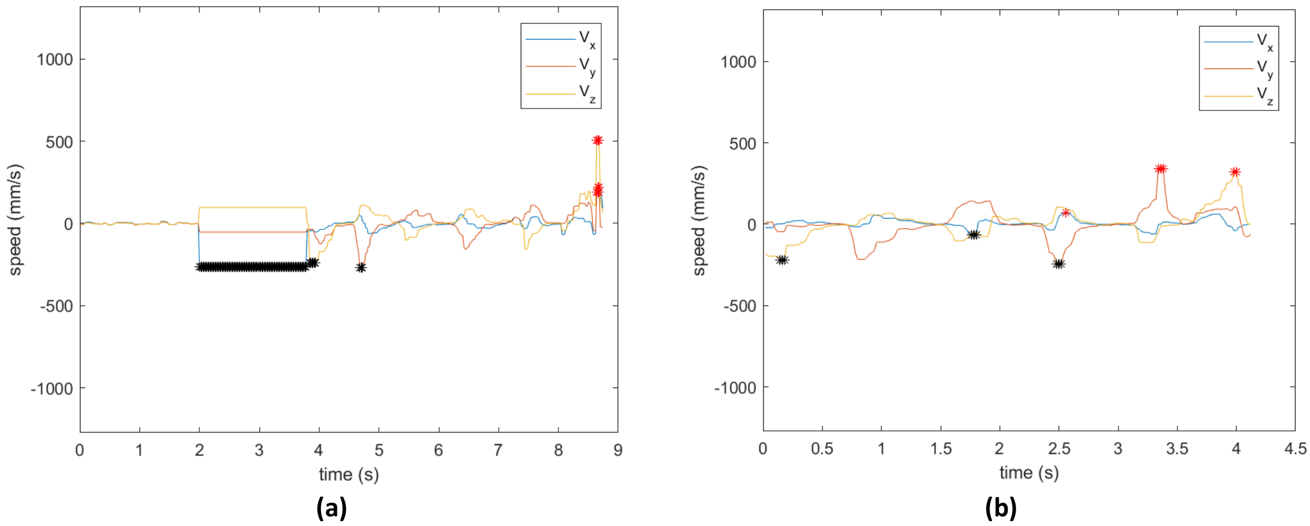
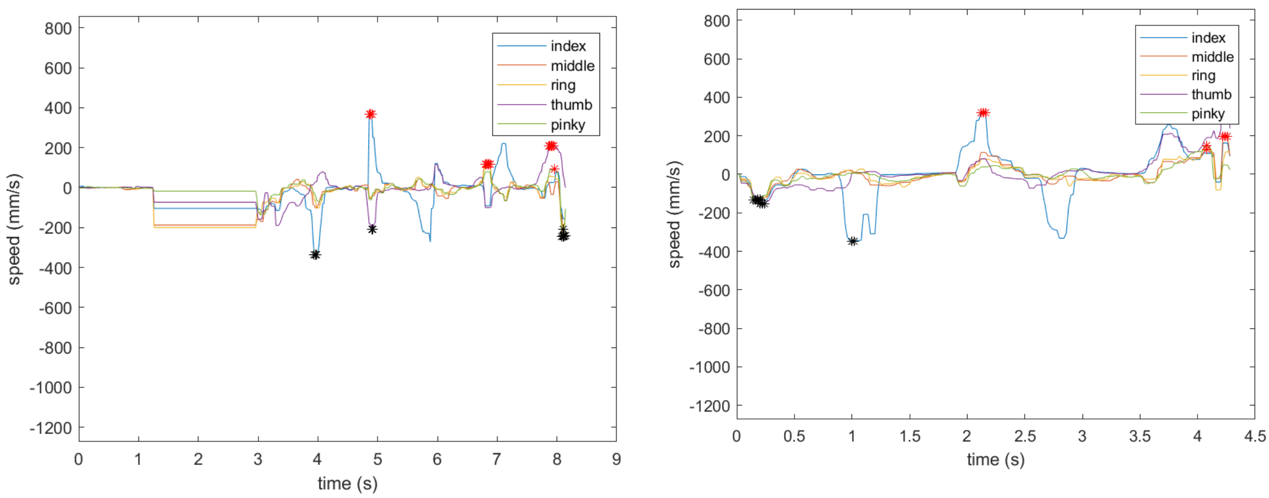
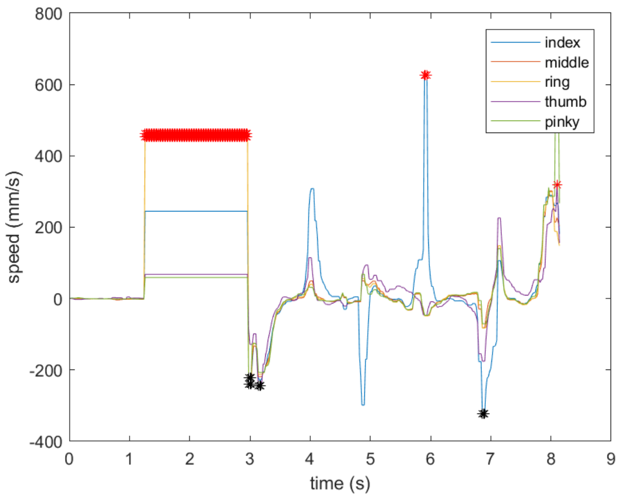


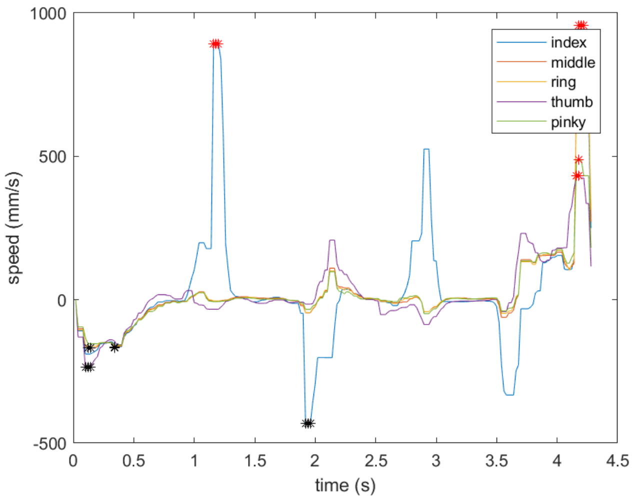
Figure 60. Exercises 5 and 6. Thumb abduction on the vertical plane for (a) left and (b) right thumb. Speed of thumb in the x, y and z directions evolution over time.

In the case of exercises 7 and 8 (pinching) (See **Figure 61**), we can see that middle, ring and pinky fingers remain quite stable and it is the index the one that moves the fastest, much faster than the thumb, which also participates in the pinching. This is coherent with the observation done in the analysis of the finger's trajectory (**Figure 45**), where the index had a greater amplitude of movement than the thumb.





(a)

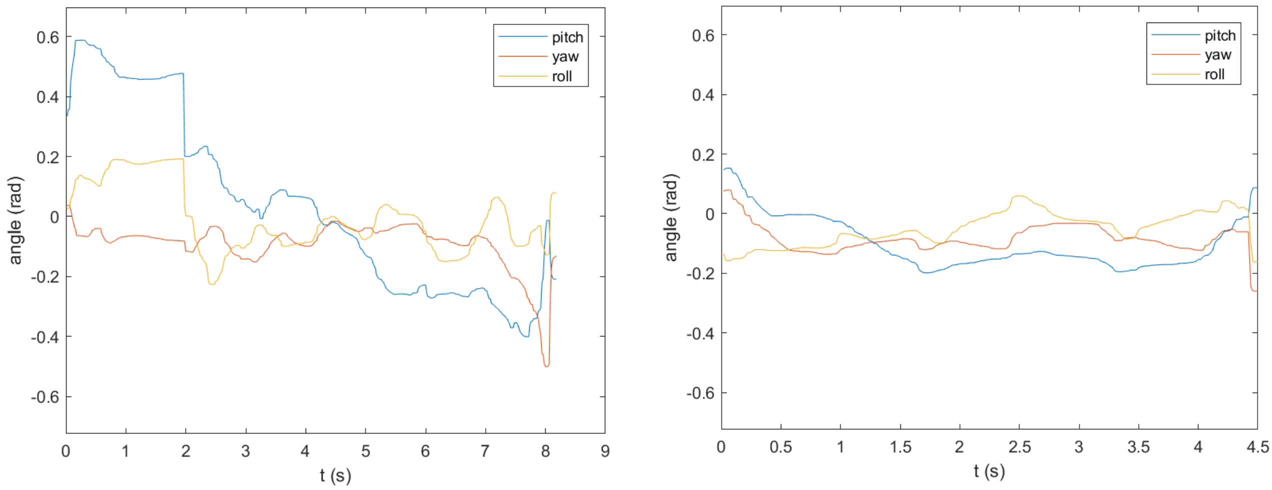


(b)

Figure 61. Exercises 7 and 8. Pinching for (a) left and (b) right hand. Speed evolution in the y (top) and z (bottom) directions.

Finally, the graphical representation of angles over time (See **Figures 62-65**) shows how the pitch angle, which indicates a movement on the YZ plane, is the one that reaches the more extreme values, whereas yaw angle, which refers to an angle on the XZ plane, is the most stable one. This is the one that most interests us, since the movement along the other directions may be a natural consequence of fingers moving. However, the yaw angle may be a measure of hand stability to be considered as well as hand center movement along the y direction. Normally, peaks coincide with the moments where the movement is being done.

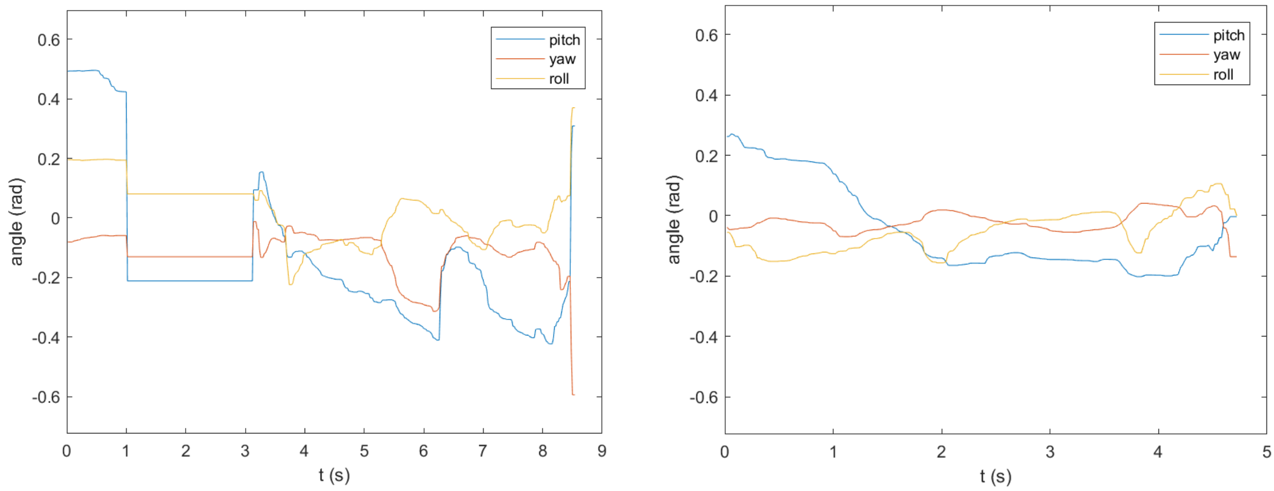
In **Figure 62**, we observe a big difference in stability between the left hand and the right one. The left hand presents a difference of 1 rad peak to peak, with continuous and sharp changes for the three angles, but specially for the pitch one. If we consider previous graphs that indicated that the actual movement of exercise 1 started at t=2 s, this peak-peak difference is reduced to 0.7 rad. However, the right hand presents a steady graph with a maximum difference between peaks of 0.35 rad. This, added to the fact that the right-hand movement is much faster, implies that the right hand remains more stable along the exercise.



(a) **(b)**

Figure 62. Exercises 1 and 2. Finger extension for (a) left and (b) right hand. Pitch, yaw and roll angles evolution over time.

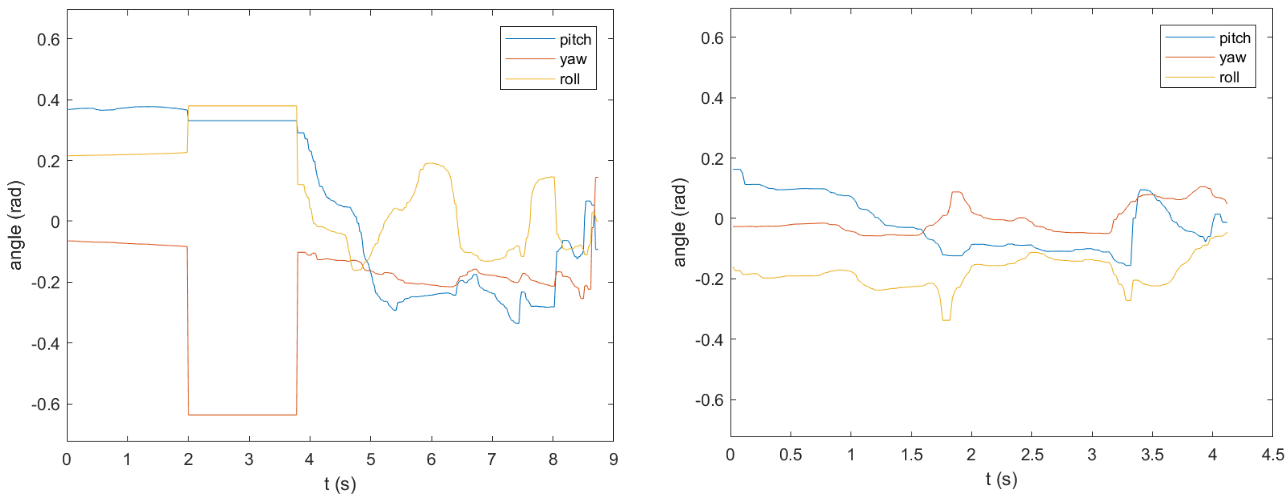
In **Figure 63** we can still appreciate a difference between the two hands for exercises 3 and 4, but this difference is smaller, because, although the left hand still presents great variations, the right hand is more instable, specially for the pitch angle. This could be produced because the abduction movement of just the thumb is less intuitive than the open-close movement of all fingers, and because when all the fingers move, the ones moving in a direction compensate the forces of those moving in the opposite direction.



(a) **(b)**

Figure 63. Exercises 3 and 4. Thumb abduction on the horizontal plane for (a) left and (b) right thumb. Pitch, yaw and roll angles evolution over time.

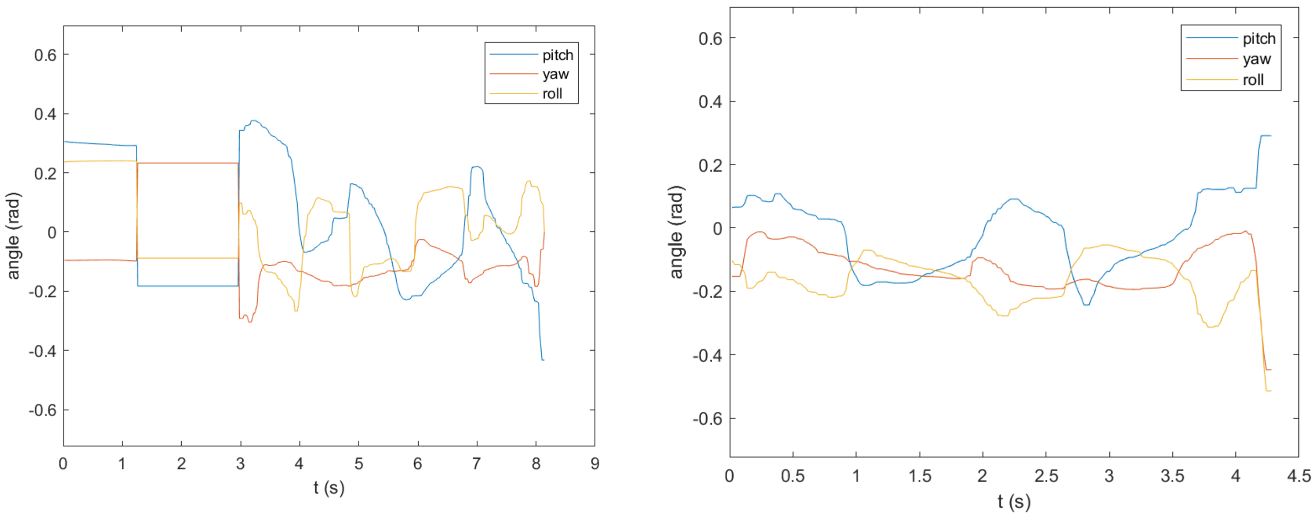
In **Figure 64**, the observations continue to be quite similar, although there are more pronounced peaks happening at the same time of the abduction in the vertical plane, specially in the left hand. This could be because this movement is even less intuitive than the previous one, and abducting the thumb vertically requires an inevitable tilting of the hand.



(a) **(b)**

Figure 64. Exercises 5 and 6. Thumb abduction on the vertical plane for (a) left and (b) right thumb. Pitch, yaw and roll angles evolution over time.

Finally, we see a different behavior in exercises 7 and 8, depicted in **Figure 65.** Although maximum differences are equal or lower than for the previous exercises (0.6 rad for the left hand and 0.4 for the right one), these changes are more frequent and sharper, implying that the pinching movement involves the whole hand. Considering how the movement of pinching requires the index moving towards the thumb, it appears normal that the pitch angle has great variations.

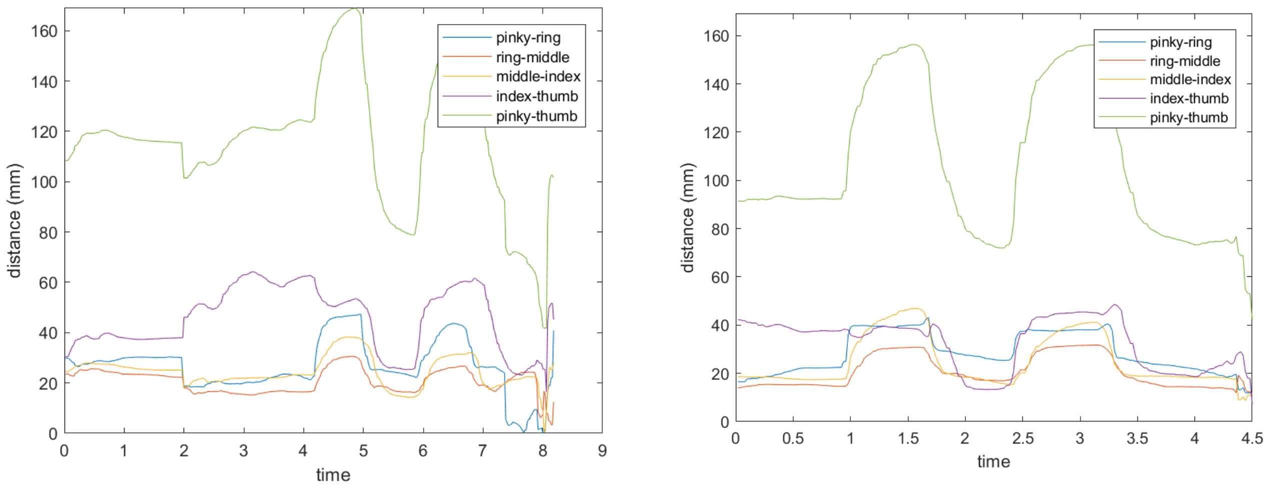


(a) **(b)**

Figure 65. Exercises 7 and 8. Pinching for (a) left and (b) right hand. Pitch, yaw and roll angles evolution over time.

Finally, we have a series of graphs applied only for certain exercises. The graph plotting the change over time of distances between finger only made sense for those exercises where all the fingers provided moved and provided useful information, these being 1,2, 7 and 8. These graphs represent the evolution of contiguous fingers' distances, as a measure of relative displacement between fingers.

Considering exercises 1 and 2, the change over time is clearly visible, with an increase of over 80 mm in the case of pinky-thumb distance for the left hand, which is a measure of total hand aperture variability (See **Figure 66**). For the right hand, this aperture is greater, with a total pinky-thumb variation of 100 mm. The rest of relative distances follow a similar curve with smaller amplitude, with the peaks occurring at the open-close moment. However, on the left hand we see one curve that does not adjust to the rest, which is the index-thumb curve (represented in purple). This curve appears to be more instable, and its variation starts before than the rest of them. Considering how it later adjusts to the other curves, this variation could be the result of the adjustment of these two fingers prior to beginning the exercise.



(a) **(b)**

Figure 66. Exercises 1 and 2. Finger extension for (a) left and (b) right hand. Distances between fingers evolution over time.

Distances between fingers was also interesting for exercises 7 and 8, since it could provide useful information about patient's pinching capability: up to what distance they are able to close the pinch, the difference between the affected and the healthy extremity and the total time they can hold the position (see **Figure 67**). For the index-thumb distances (see purple curve), we see how they reach 0 while touching, that the distance is maintained for 1 second and that it takes another second for the fingers to separate and get together again. There is a significant difference between the maximum pinch on the left hand, which is around 30 mm, and the right one, which reaches 40 mm. The most significant values are those of the middle pinch, since the ones at the beginning and the end incorporate the collocation and extraction movement, and generate a greater amplitude.

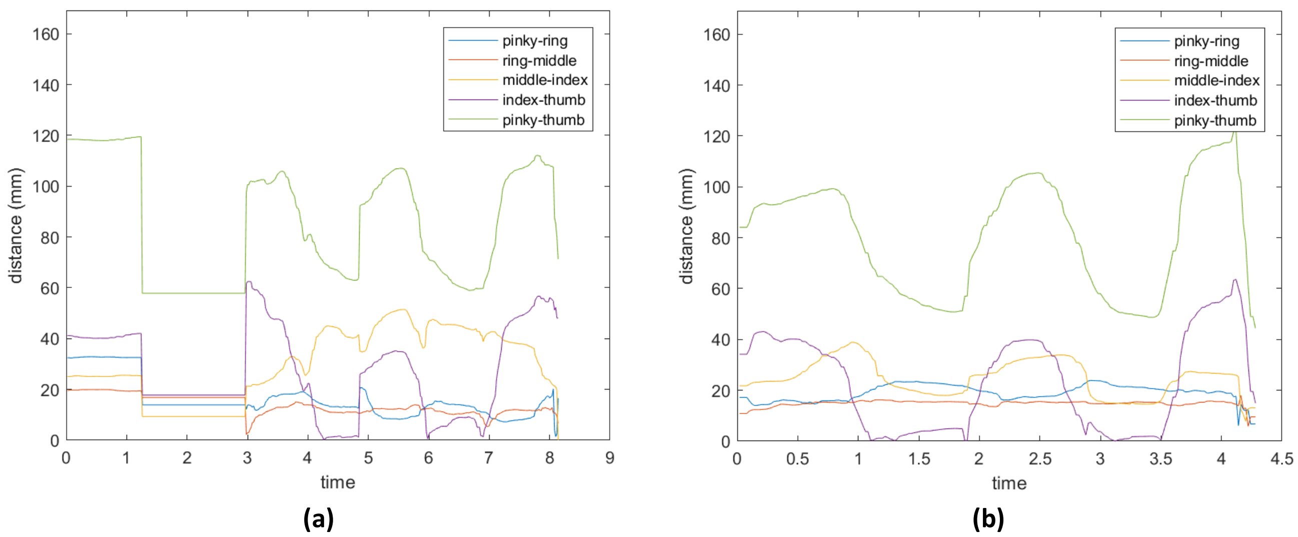


Figure 67. Exercises 7 and 8. Pinching for (a) left and (b) right hand. Distances between fingers evolution over time.

To conclude the graphical analysis, we decided to depict the variable *PinchStrength* in the pinching exercise. This variable goes from 0 (open hand) to 1 (closed pinch). In **Figure 68**, we see how it goes from 0 at the time where the distances between index and thumb are maximum in **Figure 67**, to 1, when this distance is minimum. For the right hand, it has this binary behavior, with practically vertical lines and reaching 1 completely. However, in the left hand the middle peak does not reach a complete 1, despite the distance values of the previous graph being almost identical to those of the right hand.

This could imply an imprecision of the *PinchStrength* variable, and indicate how it is more suitable to use of a specifically-created variable such as the one of distances between fingers.

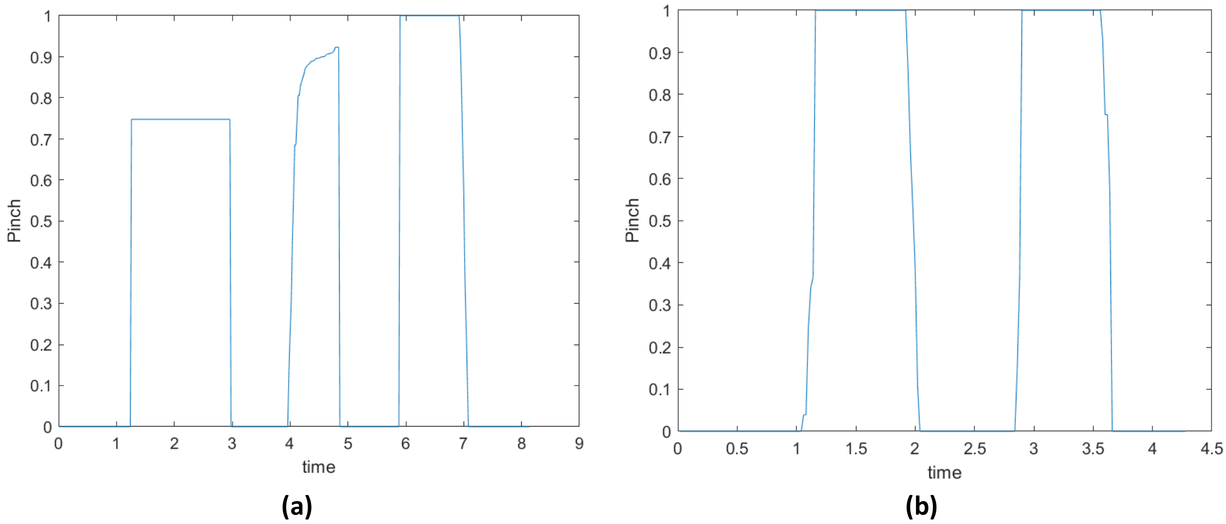


Figure 68. Exercises 7 and 8. Pinching for (a) left and (b) right hand. Pinch strength (0-1) evolution over time.

Module II graphs analysis

Exercises 9 and 10: cube dragging game

These two exercises require a different approach while analyzing for the following reasons:

- They imply an interaction with virtual reality objects, which usually requires a learning process. This means that it can take very long for patients to get used to this interaction and achieve the goal, as would happen with a healthy subject.
- Objects can fall and they may have to deviate from the gold standard trajectory, without it meaning a motor impairment.
- Everyone approaches grasping virtual reality objects differently.

These reasons were some of which were taken into account while implementing the game. For example, they were the reason why magnetic pinching was chosen over normal pinching, so that it is easier for everyone in their first attempt.

Considering all this, specific information about finger's movement or speed may not be useful, since there is no one perfect way of positioning and moving them, as long as the objective is met. Furthermore, if it took the patient several attempts to grasp a cube, which would be normal, the fingers movement representation would be messy and not useful, whereas the hand center position does provide information. With this variable, we can track the overall movement and stability of the hand, even while trying to grab the cube. That is why we chose to represent the hands' trajectory over the plane and on every direction, as shown in **Figures 69-71.**

In **Figure 69**, we get the reconstruction of the hand's center movement on the XZ plane. The most interesting observations have to do with the difference between the right and the left hand. For the right hand, we see a more precise, compact and delimited movement, held between -40 and 100 mm in the x direction, except for one peak that reaches 120 mm. However, with the left hand we see a blurrier trajectory with a higher tremor, more curved trajectories and different limits for each back-and-forth movement. We can also see how the left hand deviates in the z direction as far as 40 mm, where the right hand presents a rather constant increase along this direction, as the cubes are progressively further along z. This difference in clearness and precision of the movement can be the result of two factors:

1. The right hand is the dominant one in this particular case.
2. The game was developed using the right hand on the tests, which means that the ability needed to dominate the process was acquired by practicing.

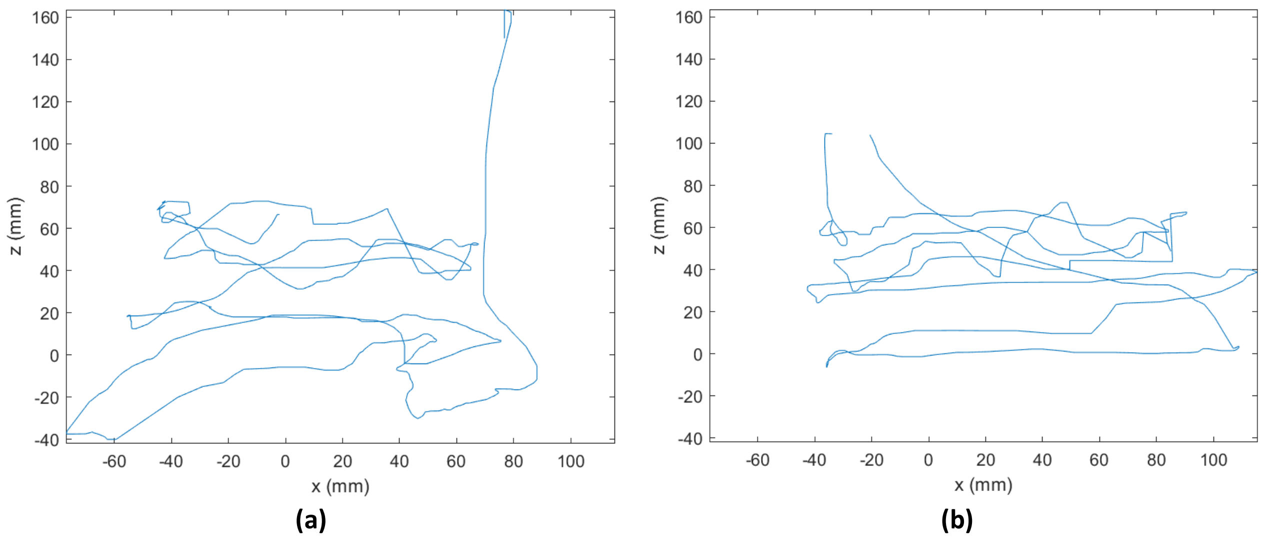
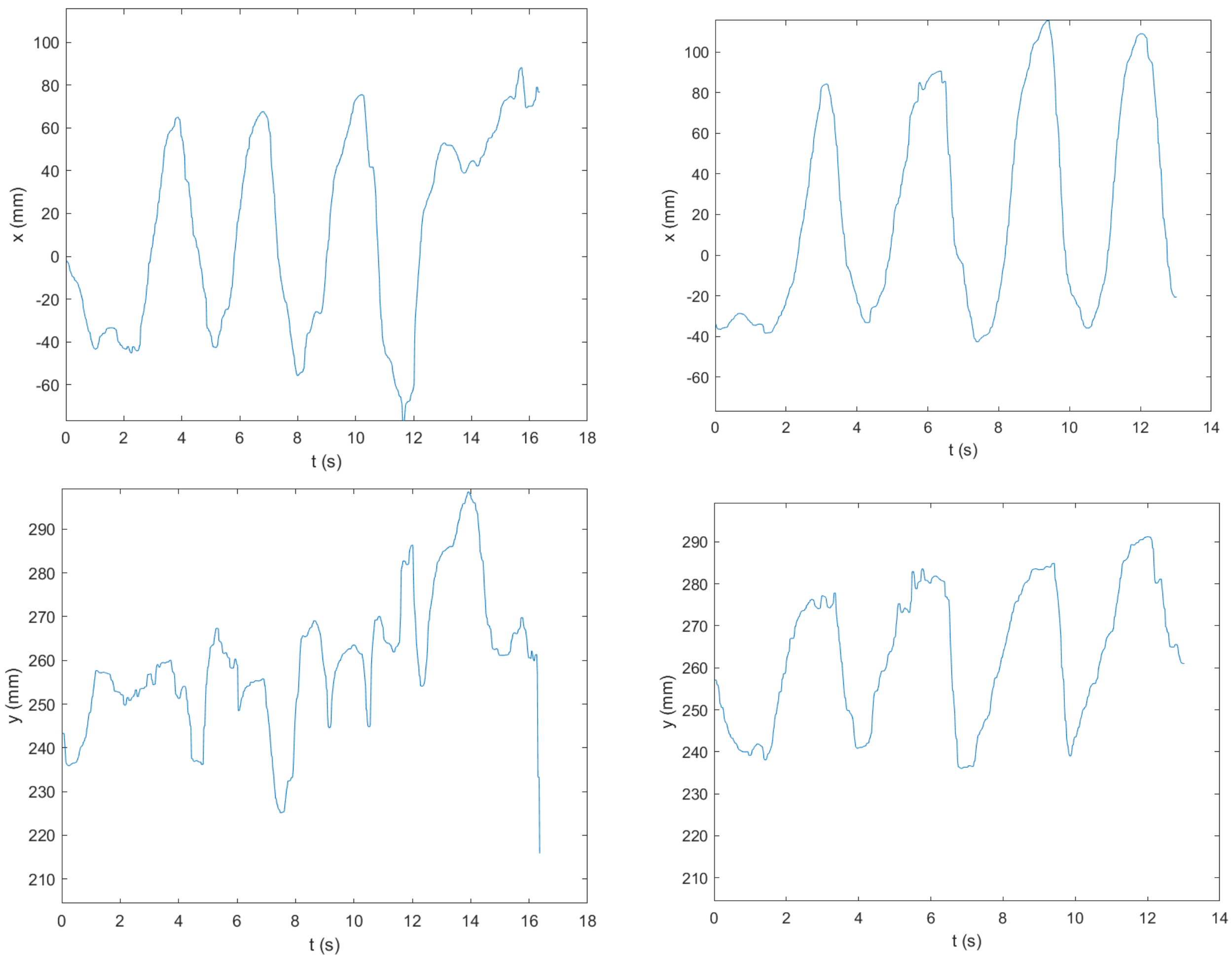


Figure 69. Exercises 9 and 10. Dragging cubes to their corresponding platform with the (a) left and (b) right hand. Movement of hand center on the XZ plane.

In the graphs shown in **Figure 70**, used to represent the trajectories of the hand center along x and y directions over time, we can perfectly see the four back and forth movements required to grab and release the four cubes, especially in the x direction. We can also see how the hand goes up and down as well four times in the vertical direction, each of the times that the cubes are grabbed.

Once again, we see a difference between the two hands in terms of noise and precision, specially in the y direction (see **Figure 70 bottom**). Whereas for the right hand we clearly distinguish the four peaks of the four times that the hand grabs the cube at approximately the same height (from 275 to 290 mm), these peaks are not seeable for the left hand, where the hand center goes up and down ten times instead of four, and with the peaks reaching different heights each time (from 260 mm to 300 mm).



(a) **(b)**

Figure 70. Exercises 9 and 10. Dragging cubes to their corresponding platform with the (a) left and (b) right hand. Hand center position evolution in the x (top) and y (bottom) directions.

Secondly, we have chosen to represent the hand center speed evolution over time on the three directions, obtaining the graphs seen in **Figure 71.** We can appreciate how the four peaks are perfectly visible for the x direction (**top**), less for the y direction (**middle**) and they disappear in the z direction (**bottom**). Besides, there is still a big difference in the clearness of these peaks between the two hands. The left hand presents a noisier evolution, with sharper peaks and with the four moments in time less distinguishable. However, for both hands we see a rather noisy image, with small peaks, that are the result of constantly adjusting the speed to perform this precision task.

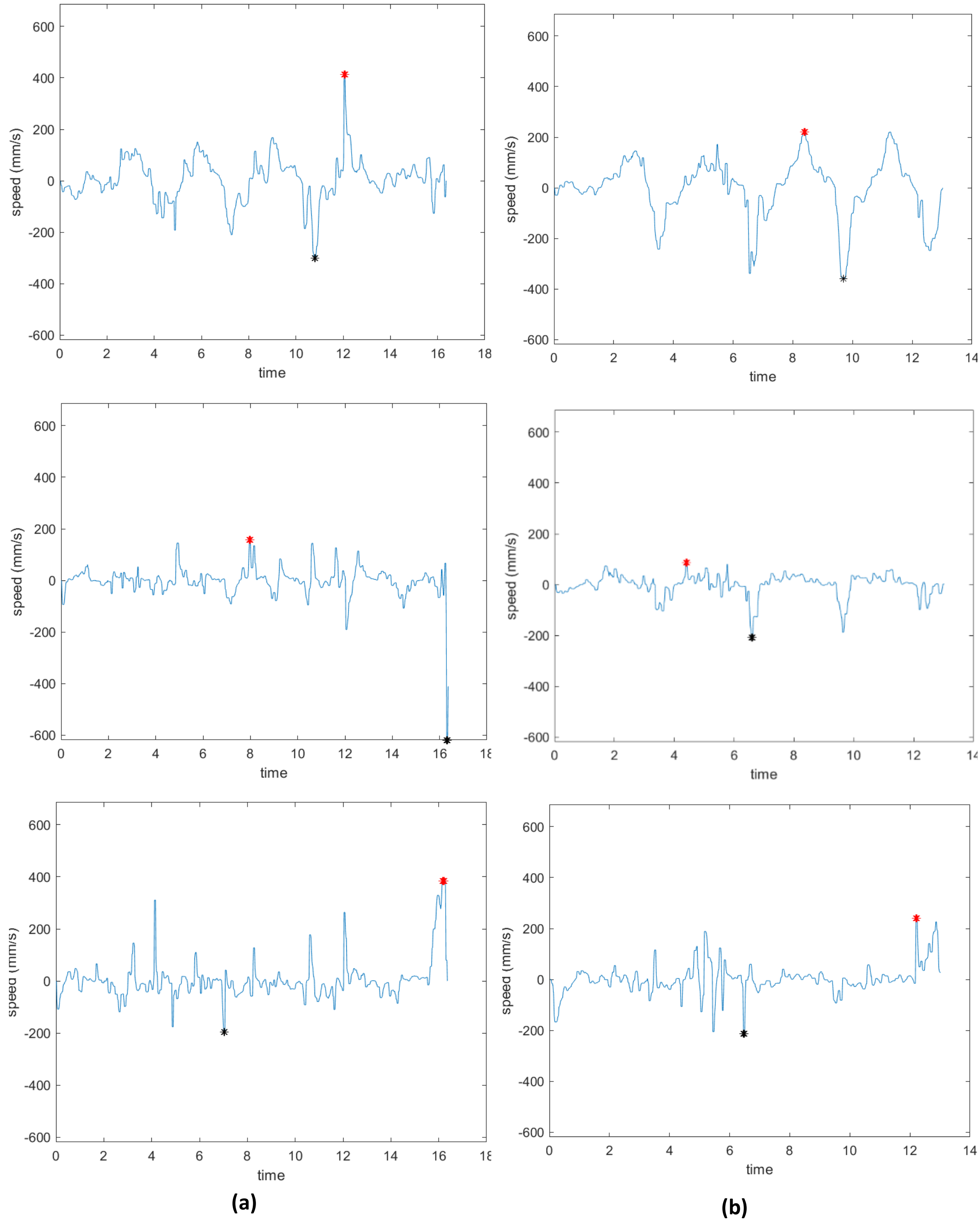
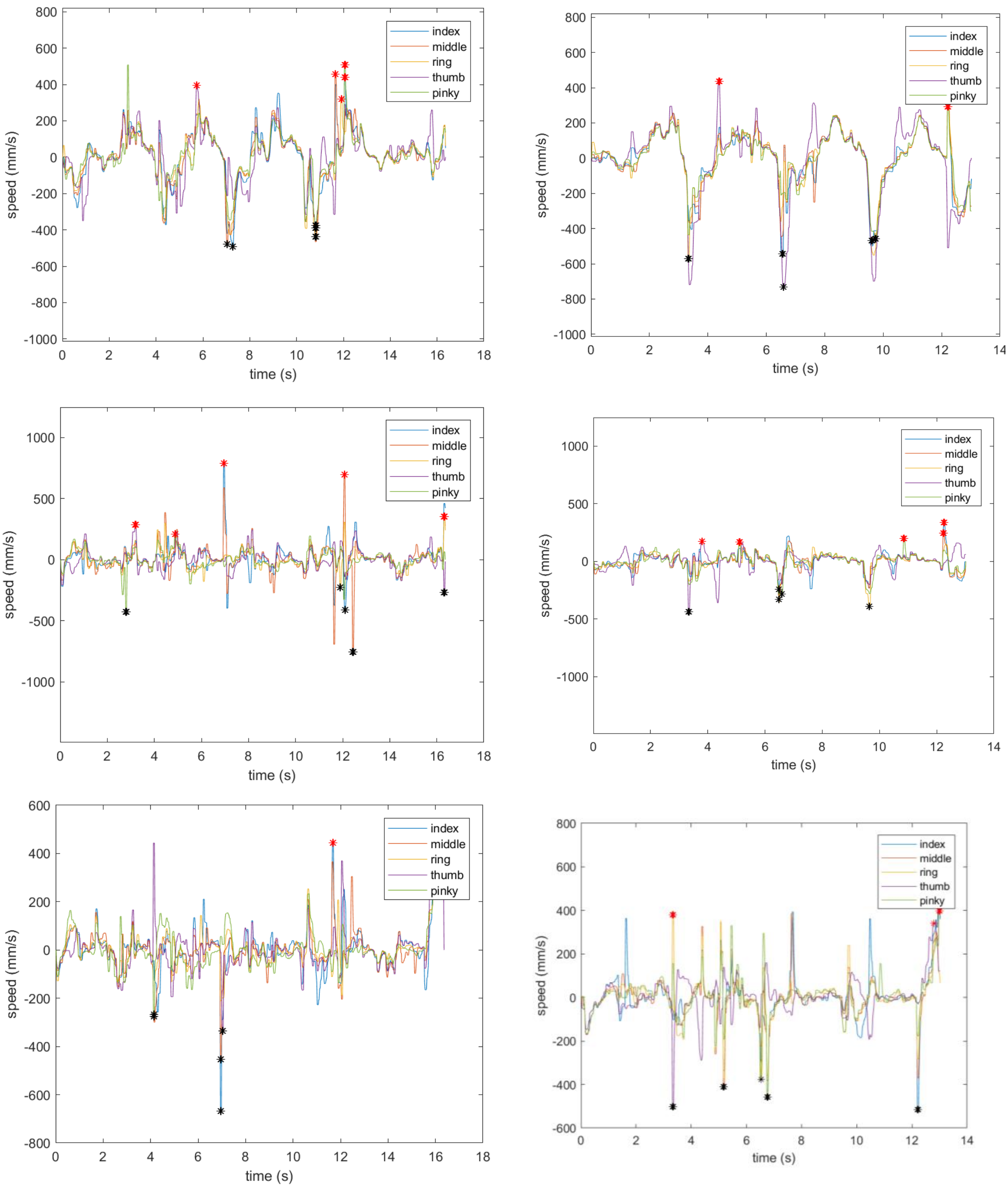


Figure 71. Exercises 9 and 10. Dragging cubes to their corresponding platform with the (a) left and (b) right hand. Speed evolution of hand center in the x (top), y (middle) and z (bottom) directions.

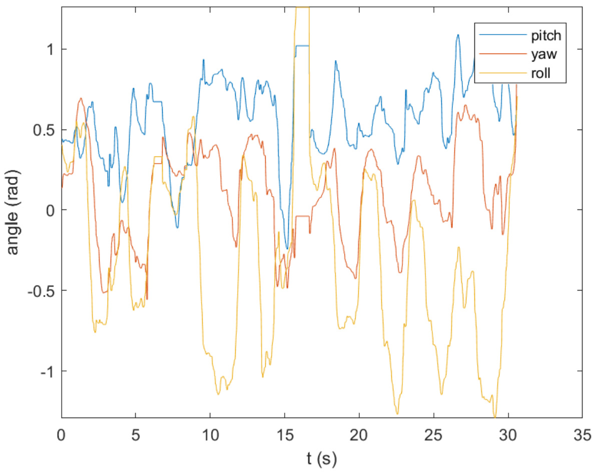
We decided to represent the fingers speed evolution over time to verify if they provided useful information besides the one just explained in **Figure 71**. Considering how this game is thought, and as previously mentioned, the fingers position may be very different from one subject to another and the need for several attempts may introduce noise, when all the information could be extracted by analyzing only the hand center speed. In **Figure 72** we can see how the underlying curve is very similar to that of **Figure 71**, but with increase noise and reduce clearness, which makes us believe that representing the fingers' speed evolution is not useful.



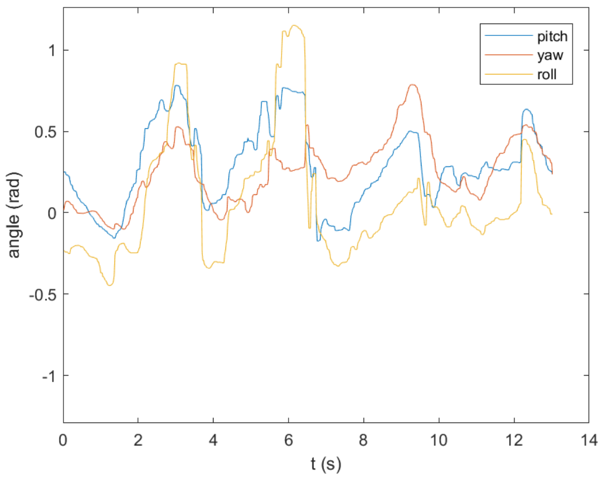
(a) **(b)**

Figure 72. Exercises 9 and 10. Dragging cubes to their corresponding platform with the (a) left and (b) right hand. Speed evolution of fingers in the x (top), y (middle) and z (bottom) directions.

Analyzing the angles evolution over time in **Figure 73**, we see the four peaks corresponding to the four movements performed in the right hand. However, for the left hand we obtain a very noisy image where little information can be extracted. Once again, this confirms how the influence of the learning rate affects the performance, this time in terms of stability and maintenance of a certain orientation of the hand. Nonetheless, the right hand also presents great oscillations and variations in the peak of each angle for each iteration (0.25 for the pitch, 1.1 for the roll and 0.3 for the yaw), which means that each time the cube is dragged with a different inclination of the hand, even if the hand is trained.



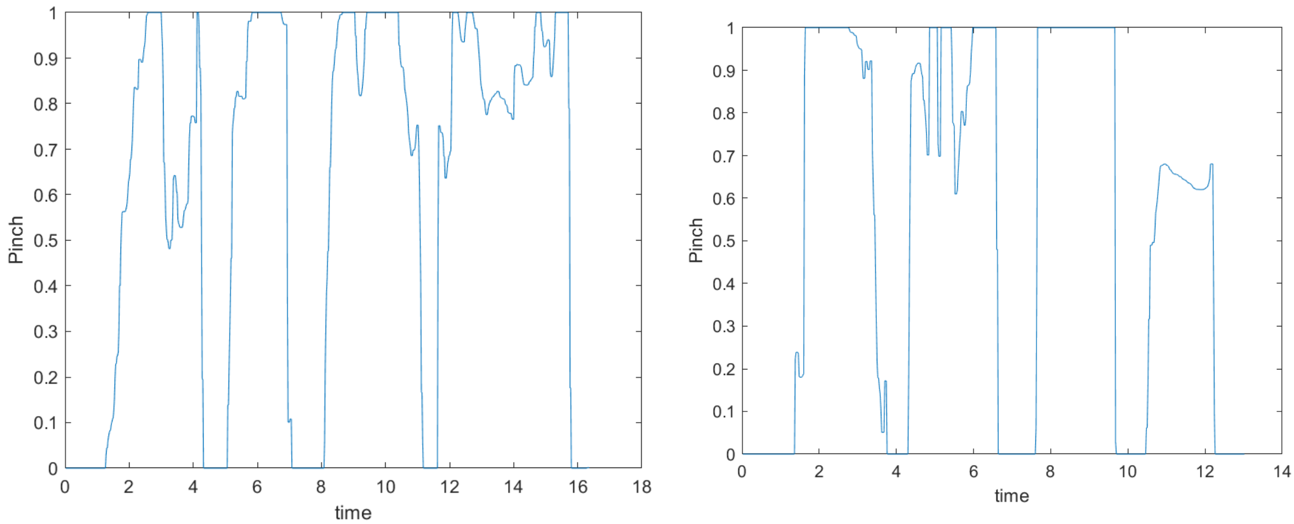
(a)



(b)

Figure 73. Exercises 9 and 10. Dragging cubes to their corresponding platform with the (a) left and (b) right hand. Pitch, yaw and roll evolution over time.

Finally, we represented the evolution of the *PinchStrength* variable, where we see four clear moments in time where the hand is pinching, lasting between 1 and 2 seconds each. In **Figure 74 left**, we see how the first and fourth pinch are not always completely closed, going up and down during the time of pinching. For the right hand, we see the same thing in the second pinch, plus how the pinch does not go further than 0.7 in the fourth one. These measures may be coherent due to the magnetic pinching, that does not require a fully closed hand to grab the cube. Moreover, the presence of a VR cube prevents the hand from closing completely, as it would happen with a real object. Ultimately, we see how the least precise pinch in the two hands is the fourth one, which makes sense considering how the last cube, which is the furthest, is the most difficult to grab, and the one that relies most on the magnetic condition.



(a) **(b)**

Figure 74. Exercises 9 and 10. Dragging cubes to their corresponding platform with the (a) left and (b) right hand. Pinch strength (0-1) evolution over time.

4.2 Results conclusions

As we were seeking, this overall analysis allowed us to validate the concept and technology developed in methods, and show the process of how to interpret the different outcomes. Graphical results were coherent with the way in which the exercises were performed, and the information represented made sense with the variables that had been collected. All the graphical representations have a good subjective correspondence to what was observed during the exercises, and allowed to formulate some hypothesis that can be contrasted in future applications. It would be convenient to use this tool on a small number of people to guarantee that it works in different cases and the obtained results are similar.

Once this is done, the module could start to be deployed and tested in the hospital environment, collecting data on pathological subjects that could start a much deeper analysis on the consequences that motor impairment of stroke patients has on their performance with virtual reality environments.

More specifically, in terms of the different analyses made, we find that differences in speed peaks may have to do with either ability to perform a movement fast, or because the patient moves at that speed voluntarily. Therefore, if we wanted to extract conclusions on the differences in speed between exercises, patients should be asked to perform the movement "as fast as possible". It is also important to consider that there are movements more intuitive than others. This is the case of abducting the thumb in the horizontal plane, which is a relatively normal movement, versus abducting it on the vertical plane, which could be considered more complicated.

Another representation that appears to be useful is the reconstruction of both hand center and finger's movement on the plane, where differences over time and between hands are easily distinguished. This variable, complemented with the trajectory along the different directions over time, gives a good and easily extracted understanding on the patient's performance.

One interesting observation has to do with the learning curve in the use of Leap Motion, especially for exercises 9 and 10. The difference observed between the trained hand versus the untrained one, showed that it might be a good idea to have a practice round where the patient gets familiarized with the process, and then do the actual recording, so that results are not too influenced by unfamiliarity to movements.

Referring to the previously mentioned fatigue effects, even if all subjects, healthy or not, experience them, pathological ones could have a more drastic deviation from the original point. It would be interesting to extract the curve slope in the hand center's vertical decay, and compare the statistical behavior of it for healthy patients and for those with motor disorders.

Another point that could be implemented is to ask patients to hold a certain position and analyze the results: time they are capable of maintaining a perfect position (pinching, for example, because of its importance in daily life), progression of the fatigue effects in terms of deviation, reduced speed or variation in angles.

Finally, one of the main observations extracted from the analysis is the significant difference in performance between the two hands. To differentiate between the effects of practice and the effects of the dominant hand versus the non-dominant one, studies should be made with untrained versus trained patients, and left-handed versus right-handed.

5 Conclusions and prospects

5.1 Conclusions

This MSc Thesis was developed to cover an existing need in society to develop a precise diagnostic tool that rely on objective measurements of the hand for people affected by motor impairment caused by stroke. Considering the increasing incidence and incredible burden that this disease represents, this project is aimed at having a high impact in the clinicians' and patients' daily life. By incorporating novel technologies such as VR, we can take advantage of these new discoveries by giving them a clinical use. To achieve the overall objective of this MSc Thesis, a series of subobjectives and milestones were defined and covered along the way. The consecution and conclusions extracted from each step, allowed to progress until the final goal was achieved.

Firstly, the research on the physiopathology of stroke gave an understanding of the degree of affectation these patients suffer, and the ways in which they are impaired. Analyzing the way in which clinicians assess the overall health status of the patient, and in particular the affectation of their motor skills, an idea on how to approach the process was born. It is crucial to keep in mind that this type of tools must be developed considering doctor's inputs all along, comprehending their needs and current lacks. The different scales used in the clinical environment, such as ARAT, NIHSS or Wolff, served as examples on the types of exercises that neurologists use on patients to determine their hand function. With this initial research step, the first subobjective was met: "Understanding of the gaps not covered by current diagnosis methods in the assessment of hand motor loss after stroke".

Considering how the goal was to incorporate VR technology in said diagnostic process, the next step required a thorough analysis on the state of the art of virtual reality, in particular with clinical purposes. The conclusions extracted from this phase showed how the main field in which VR is being used is neurorehabilitation. Furthermore, there have been studies using Leap Motion in this area that served as an example on how a clinical study should be conducted, and the type of exercises that were used. However, there are not enough studies of VR for stroke patients that allow to conclude the effects of this technology. Furthermore, it was observed that all the papers and studies found are orienting VR with rehabilitation purposes, and none were found that used them as a diagnostic tool.

The research on VR technology set Leap Motion as the most adequate tool, due to its low cost, constant tracking and freedom of movements. Moreover, the variables provided by Leap Motion allow to extract all the desired information to analyze later. However, during the process some imprecisions were found, such as when it detects one hand instead of the other, or the hand turns upside down, or it is not registered for several seconds. It appears necessary to carry out a deeper study to extract Leap Motion's precision and reliability for this specific use case. Finally, considering how Unity is the standard platform in game development, with a special focus on VR, and how Leap Motion easily integrates with it, choosing to implement the environment with it was adequate.

Once the ground conditions were stablished, the exercises to be implemented were defined with the inputs taken from clinicians. From this, it was understood that the most important elements to be measured were thumb function and fingers mobility. However, considering the usual exploration doctors do, Leap Motion does not allow to incorporate them fully. Such is the case of exercises that use external forces executed by doctors or external elements to be grabbed. This appears as a drawback on the use of Leap Motion, since a full evaluation requires also those tasks. However, more complex processes can be tested in further development of this environment, and new ways can be found to measure the same things that are measured nowadays with traditional methods. After this stage, the third subobjective of the MSc Thesis was covered: "Definition of a series of exercises in collaboration with neurologists and replicate them in a virtual reality environment".

With the development of a support system that incorporated the patient's needs as well as the technical requirements of the Leap Motion controller, the fourth milestone was met: "Definition of the physical conditions for the appropriate performing of the exercises". While analyzing the sufficiency of this support system, it appears necessary to mention how for a healthy subject who is able to hold their hand, doing the exercises with the system is rather uncomfortable, and the movement is less intuitive. However, this last point has to do with the fact that the hand's movement is affected by the arm, that always effects some kind of force. The testing of the system allowed to verify that no compensating force can be applied with the arm while using it, and how it keeps the hand over the right position, which is what it was intended for. A more sophisticated design should be implemented. Probably, the most adequate way to do so would be with a 3D printer, that allows easy, fast and cheap iterations.

Once the implementation began in Unity, it was soon understood that the best way to collect data on patient's behavior with the purpose of obtaining a constant monitoring, is to use Leap Motion's own internal variables associated to the hand controller object. This covered the fourth subobjective "Definition of a way to collect detailed information on the patient's hand while performing the exercises". However, the hierarchization of these variables requires an intricated process where variables have to be created each time, and in a different way depending on the structures that are being detected. This point may be up to being improved and optimized, since the criteria followed to write the code was that it was functional and did not use unnecessary variables so that there would not be slowdown problems.

Subsequently, by unifying Leap's variables to the Unity's objects through scripts, a functional game-like environment was created, achieving the fifth subobjective "Development and implementation of a virtual reality environment", which was the core of this project and the point that took up the most effort. This environment was developed with the purpose of being easy to use both by patients and clinicians, as well as functional. The division into two modules will allow to test two different applications of VR for stroke patients: the first one replicates normal movements that clinicians evaluate daily, with the only difference of them being tracked and recorded, offering the possibility of analyzing it afterwards; the second module introduces VR interaction to see how patients behave while being stimulated in a different way, in a more engaging and different environment. Considering how there is a learning rate, especially for the second module where patients must learn to grab the cubes, this second approach may have more of a rehabilitation usability rather than diagnosis, but it can't be said until tested on the clinical environment.

The fifth objective "Data collection on control subjects and stroke patients" could not be fully met due to the Covid-19 restrictions occurring at the time. The alternative was to extract data on a single subject to verify its functioning and compliance to what was conceived. This point must be covered in the future in order to properly validate the technology, since the data used for the analysis was done in a controlled environment, using the most representative example, by a healthy subject who controlled and understood the use of Leap Motion and the environment. Using it on stroke patients, at a more variable environment and by people, both clinicians and patients, who are not experts in its use, may provide very different results that create new needs and that helps identify possible mistakes.

Finally, the analysis of the generated files allowed to check the coherence of the collected data, as well as to design a way to systematically analyze the results extracted. With this last step, the last subobjective was met "Extracted data analysis". Despite Matlab being a rather academic environment, the designed tool appears appropriate to be used in the clinical environment. Just by running the code, doctors can extract the graphs, whose interpretation are intuitive and, in some cases, provide information at first sight. The tables output might require a further development with a more powerful analysis tool, once more information is collected. The absence of study subjects did not allow to extract definitive conclusions, but the hypothesis posed settle the ground for later use of the environment and the analysis tool, since the graphical analysis seemed to be coherent with what was expected. Some of these hypotheses go beyond the original idea that there will exist a difference in performance between healthy subjects and pathological ones. It appears plausible that there is a significant difference between dominant and non-dominant hands, as well as a much better performance if the exercises have been previously done, especially those of the second module. These observations should be considered while using it at the hospital, and it poses some questions such as if the patients should get a practice round before collecting data on their performance.

To conclude, as a result of all the previous milestones being reached, the overall goal of this MSc Thesis has been met. We have designed a VR environment using Leap Motion's technology, following the requirements of neurologist's and constraints presented by stroke patients, in order to obtain objective measures on patient's performance, that could be linked to their health status.

5.2 Prospects

The next steps that should be followed if this project was to be continued, would begin with the testing in a greater population to find possible improvements and pose more hypotheses that could orient the clinicians and analysts works once a clinical study begins. Followingly, a proof of concept should begin at the hospital, to guarantee its proper functioning and suitability without the need of bothering many patients. Finally, once the technology has been completely validated and new improvements incorporated, a big scale study on patients should take place. This study would serve to analyze the impact of VR on stroke patients' diagnosis. Moreover, it should look to contrast the hypothesis formulated in the graphical analysis of this MSc Thesis, as well as the ones that had been formulated in the following tests:

- Differences in performance between healthy and pathological subjects.
- Differences in performance between dominant and non-dominant hand.
- Differences in performance between trained and non-trained subjects.
- Effects of fatigue in a more prolonged movement, by asking to hold a certain position or to repeat the exercise a greater number of times.

Another improvement line that should be implemented prior to the hospital implantation, would be to create a more sophisticated support system. This system could be created with 3D printers so that iterating until reaching a final model is easy. The final system should be portable, cheap, comfortable, besides complying with the technical requirement explained in this document.

Finally, it appears appropriate that every new case that generates information is recorded for a later analysis on what Leap Motion registers on the interface, versus what the subject is doing, and contrast these pieces of information with the data collected and analysis results. This way, there will be a more detailed information on Leap Motion's accuracy and constraints, and noise coming from the subject will be distinguished from noise generated by Leap Motion registration.

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Annex A: Ethical, economic, social and ambiental aspects

A.1 Introduction

This MSc Thesis has been developed in the context of a collaboration between the Neurology service at the University Hospital La Paz and the Robotics and Control department at ETSIT. It aims to cover a found need of implementing a precise diagnosis tool based on objective measurements for stroke patients in terms of hand mobility. To create it, it was decided that the most suitable technology was the Leap Motion controller, a low-cost portable device that allows to create virtual reality environments with which users can interact life-like.

The affected groups are two: patients having suffered from stroke, who can benefit from a more engaging and precise diagnosis method to improve their recovery; and clinicians who can benefit from a better understanding of the patient's conditions, to better orient their treatment.

Considering how stroke is the second cause of mortality worldwide, the first cause of disability and second for dementia [1], this disease represents one of the greatest burdens in terms of economic, healthcare system charge and expenditure, and social implications. In Spain, stroke is the first cause for death in women, and the second overall cause of death [2]. Considering how the life expectancy is increasing, and how one of the main affecting factors is old age, stroke may have an increasing impact in today's society.

Considering our specific focus on motor affectations of the hand, it is important to note how up to 85% of patients suffer from hemiparesis as a symptom after acute stroke, which reduces mobility of the hand or the whole arm in the affected side of the body. This is one of the most difficult functions to fully recover, and at the same time it is one of the most impairing, affecting several aspects of patient's daily life [3].

A.2 Description of relevant impacts related to the project

The greatest impacts expected from this project are social, clinical and technological. With the implementation of this VR tool in the hospital environment, we expect to improve patients' lives by obtaining a more precise diagnosis even for the most complex cases, as well as clinicians' lives by easing their work. Moreover, by introducing new technologies such as VR, we expect to contribute to the digitization of the clinical world, which can become a revolution in the way healthcare is provided.

A.3 Detailed analysis of some of the main impacts

- **Clinical impact**. Improving the diagnosis method in such a prevalent disease as stroke is translated into a improvement of the whole stroke management process. A better diagnosis implies less time at the hospital in the beginning, and afterwards less need for rehabilitation and hospital resources in general, such as clinician's time. Moreover, by improving their condition with an accurate diagnosis, we avoid them having a worsening of their condition that would affect both patients and the hospital environment.

- **Social impact**. By obtaining an overall better diagnosis and treatment, we can create a better outcome after stroke. We can improve patient's quality of life by increasing their independence and allowing them to perform daily tasks.
- **Economical impact**. We aim to reduce the economic burden of stroke in terms of dependency and worsening of condition. By doing so with a low-cost and portable device, we are contributing to reduce expenditure and optimize workflows for patients, who do not have to rely on costly sessions, and hospitals, who do not have to dedicate human resources to this task, and can dedicate it to others.
- **Environmental impact.** Since this tool can be used and expanded as a rehabilitation tool, preventing patients from having to displace to the medical center to undergo rehabilitation will reduce the pollution associated to transportation.
- **Technological impact.** By introducing edge technologies such as VR in the hospital environment, we can contribute to modernize processes, and improve patient's and clinicians' lives. Furthermore, we would be contributing to a more friendly experience in such a complex condition. Once this tool has been introduced and has been proven useful, the mindset and general beliefs around introducing new technologies in the medical environment may change, allowing for more disruptive discoveries to change the way in which healthcare works.

A.4 Conclusions

This project is ultimately aimed at improving peoples' lives, either stroke patients or clinicians, which makes the clinical and social impacts very relevant while analyzing this MSc Thesis. We have seen that, when we impact such important areas as health, in a disease that has such a great incidence and burdens associated (economical, quality of life, clinical), we indirectly create multiple impacts in other areas. Such is the case of economic impacts in terms of reducing overall clinical expenditure for stroke patients, as well as reducing rehabilitation costs both for patients and institutions; or social by improving patient's independency; or even environmental, by providing a way to keep up with daily rehabilitation sessions without having to displace to the center.

Furthermore, I believe that introducing new and disruptive technologies in our healthcare systems, which are some of the great institutions that are the least digitized, we can impact profoundly the way healthcare is provided, affecting society as a whole, improving clinicians workflows and increasing patient's life expectancy, with an optimized process that begins with prevention, and continues all along through diagnosis, treatment and rehabilitation.

Annex B: economic budget

Here below is a detailed description of the expenditure associated to the development of this MSc Thesis. In **Table 5,** we can see the expenditure derived from Human Resources. In **Table 6**, we have a detailed description of material resources cost, including software.

	Cost/hour (€)	*Hours*	*Total (€)*
Engineer tutor	60	30	1.800
Medical tutor	60	15	900
Engineer student	30	375	11.250
TOTAL			**13.950**

Table 5. Human resources budget

	Price (€)	*Time of use (months)*	*Amortization (years)*	*Total (€)*
Personal computer	1.200	6	5	120
Leap Motion controller	100	6	5	10
Support system materials	Free (recycled)	3	-	0
Unity software	Free	6	-	0
Matlab software	Free	2	-	0
TOTAL				**130**

Table 6. Material and software resources budget.

We obtain the total budget by adding the personal and material costs and including the taxes applied in Spain, as shown in **Table 7**:

	Cost (€)
Human resources	13.950
Materials and software	130
Taxes (IVA) (21%)	2.956,8
TOTAL	**17.037**

Table 7. Total budget.

Annex C: clinical user guide

The following steps need to be followed to use the virtual reality environment, collect the data and extract the corresponding tables and graphs.

1. Install Unity version 2018.4.14f and Matlab R2017b or later.

2. Save the Unity executable VRStroke and Matlab files (*AnalysisTool.m, DataAnalysis.m* and *comma2point_overwrite.m*) in the same folder, wherever the information is most convenient to be kept. Here is where the files created during the game will be created and where Matlab will store the graphs and tables.

3. Place the user in the right position using the support system, defined in Chapter 3 (Technical Requirements).

4. Plug in Leap Motion controller.

5. Execute the Unity environment.
    a. Insert patient data
    b. Click start
    c. Follow instructions on screen to guide patient's movement. Once the exercise has been done, as considered by the clinician, click *Next* button.
    d. Once all exercises have been done, click *Finish***.**

6. Open Matlab file « AnalysisTool.m » and click *Run*.

7. Wait until the execution is over and check that the images and tables have been properly saved in the working folder.

Annex D: developer's handbook

1. Installation and getting started

1. Download Unity version 2018.4.14f

2. Configure Leap Motion Controller:
    a. Go to leapmotion.com/setup and download LeapMotion SDK controller version 2.3.1
    b. Plug device into computer.
    c. Execute LeapMotion installer.
    d. Fix Windows 10 incompatibilities by substituting modules at Program Archives within the computer. Substitute the modules LeapSvc.exe and LeapSvc64 by the ones provided at: https://forums.leapmotion.com/t/resolved-windows-10-fall-creators-update-bugfix/6585

3. Import Leap Motion Core Assets package for version 2.3.1
    a. Open Unity Hub
    b. Create new Unity Project
    c. Assets → Right click → Import packages → Custom packages → LeapMotionCoreAsset_2_3_1.unitypackage. Obtained at GitHub: https://github.com/leapmotion/LeapMotionCoreAssets/releases?after=prerelease-v2.4.0
    d. Explore provided Scenes and examples.

2. General environment description

Objects:

- Main camera: its location determines what the user sees on play mode.
- Hand controller: its relative colocation is important to guarantee proper interaction and visibility.
    - Physical Model:
    - Graphical Model:
- Canvas
    - Buttons: configured to trigger *MenuScript.cs* different methods on click. They change color on placement of the mouse over the button.
        - Siguiente (next scene)
        - Anterior (previous scene)
    - Explanation text
    - Example images

Scripts used:

- *MenuScript.cs:* creates different functions that, associated to the buttons, allow to pass to the previous or next scene.

- *InputData.cs:* creates a folder using the name introduced in the menu of patient data management.

In order to have the created scenes in the exported file and that the index built on MenuScript can work, we need to load them on the environment. File → Build settings → Drag the desired scenes on the main window.

3. Position tracking

To print the desired variables, the scripts used are two:

- *PrintData.cs:* extracts the Hand object from the current frame and, using the Leap Motion's hierarchical structure, defines all the variables: tip position and speed for each finger, hand center position and speed, grab and pinch strength, angles and lifetime of hand object. It is important to note that the variables are separated by right or left.
- *LeapData.cs:* fills the values of the variables created in *PrintData.cs,* updating each frame. It separates the variables that are Vector3 (position and speed) into single variables (x, y, z). Then, it transforms the variables to strings so that they can be later printed. It defines what variables are called in what exercise. It creates a file with the name of the exercise, a first line with the name of the variables printed, and then prints the content at a rate of 0.02 seconds during the whole time that the exercise is on.

To sum up, data is extracted in *PrintData.cs* script, and it is printed into a file in *LeapData.cs* script. *LeapData.cs* calls variables created in *PrintData.cs* and creates the variables to be printed for each exercise.

5. Game (scenes 9 and 10)

This game has been partially developed using Leap's example Scenes. In particular, the one called "Magnetic Pinch". This way, we have objects created with Leap's interaction requirements. We have the following sets of objects, besides the main camera and light:

- Cubes: interactable assets, all of the same shape and size but different colors.
- Platforms: these platforms are fixed in all their coordinates so that the hand does not displace them while playing. Each one corresponds to one cube of the same color.
- Targets: these objects are placed in the center of each platform, so that we have a visual help big enough (the platform) and a smaller one so that the objective is to place them in the middle of the platform. To this target is to which the cubes are attracted by creating a gravity force from one to another through the script Attraction.
- Confetti: Particle System placed over each target deactivated by default. It is linked to the script Destroy, so that is activated when the cube reaches the target.

Scripts created (some of the used scripts are those that come by default with Leap's Objects; the most important one is MagneticPinching, that defines the way the hand can grab objects):

- *Counter.cs*: it modifies the text in the Text object passed as reference. It creates a counter that increments seconds so that the player can keep track of the time spent.
- *Attraction.cs*: it creates a gravity force from the target to the cube (*attractedTo*). The purpose of this interaction is that the cube is helped towards the target and it is not thrown far away because of the instabilities of the pinching.

- *Destroy.cs*: it deactivates the cube once it reaches a certain distance to the target. It is also used to activate the confetti object once the player covers an objective.

6. Analysis tool

The following tool was developed with Matlab. It uses four different scripts:

- *Comma2point_overwrite.m*: it changes the decimal comma with which numbers are printed in Unity, to the point comma that Matlab reads as double.
- *Dataanalysis.m*: applies the previous function for each exercise, saving it in another file so that original data is not affected and to have a shorter name, and gives as output a table extracted from said file.
- *Graphlimits.m:* finds the maximum and minimum values for each variable and creates the limits for the graph representation based on that, so that Matlab does not automatically adjust the graph limits to the content of the variable and results are comparable in scale. Modules 1 and 2 limits are differentiated because of the different nature, that makes the ranges of motion and speed very different.
- *Analysistool.m:* it is based on a for loop that goes from exercise 1 to 10 until all the variables and all the exercises have been analyzed. It calls all the previous functions. It is based on the table created with *Dataanalysis.m*. The first step is to clear the lines in the beginning and end that do not give useful information and do not change. They are erased analyzing the differential of each line, so when it's equal to zero it is descarded. Secondly, it filters high frequency noise by applying a one dimensional fifth order median filter. Once the table has been filtered, the variables are extracted differently for the different exercises, since the name of the variables are different, and because different exercises have different variables. Then, it creates the variables for the tables, such as the maximum difference of coordinates or the time needed to perform the exercise. Finally, it represents the variables as wished, stablishing the graph limits extracted from *Graphlimits.m*, and creates the tables with the most important variables.

To use this tool, the last script is the only one that has to be run, because the functions defined in the three other scripts are automatically called from it.

Annex E: variables included for each exercise

	1	2	3	4	5	6	7	8	9	10
left_index_x	x						x		x	
left_index_y	x						x		x	
left_index_z	x						x		x	
left_middle_x	x						x		x	
left_middle_y	x						x		x	
left_middle_z	x						x		x	
left_ring_x	x						x		x	
left_ring_y	x						x		x	
left_ring_z	x						x		x	
left_thumb_x	x		x		x		x		x	
left_thumb_y	x		x		x		x		x	
left_thumb_z	x		x		x		x		x	
left_pinky_x	x						x		x	
left_pinky_y	x						x		x	
left_pinky_z	x						x		x	
right_index_x	x						x		x	
right_index_y	x						x		x	
right_index_z	x						x		x	
right_middle_x		x						x		x
right_middle_y		x						x		x
right_middle_z		x						x		x
right_ring_x		x						x		x
right_ring_y		x						x		x
right_ring_z		x						x		x
right_thumb_x		x		x		x		x		x
right_thumb_y		x		x		x		x		x
right_thumb_z		x		x		x		x		x
right_pinky_x		x						x		x
right_pinky_y		x						x		x
right_pinky_z		x						x		x
rightStrength		x		x		x		x		x
leftStrength	x		x		x		x		x	

leftPitch	x		x		x		x		x	
leftYaw	x		x		x		x		x	
leftRoll	x		x		x		x		x	
rightPitch		x		x		x		x		x
rightYaw		x		x		x		x		x
rightRoll		x		x		x		x		x
leftHandCenter_x	x		x		x		x		x	
leftHandCenter_y	x		x		x		x		x	
leftHandCenter_z	x		x		x		x		x	
rightHandCenter_x		x		x		x		x		x
rightHandCenter_y		x		x		x		x		x
rightHandCenter_z		x		x		x		x		x
rightHandSpeed_x		x		x		x		x		x
rightHandSpeed_y		x		x		x		x		x
rightHandSpeed_z		x		x		x		x		x
leftHandSpeed_x	x		x		x		x		x	
leftHandSpeed_y	x		x		x		x		x	
leftHandSpeed_z	x		x		x		x		x	
rightPinch		x		x		x		x		x
leftPinch	x		x		x		x		x	
lifetimeOfRightHandObject		x		x		x		x		x
lifetimeOfLeftHandObject	x		x		x		x		x	
left_index_Vx	x						x		x	
left_index_Vy	x						x		x	
left_index_Vz	x						x		x	
left_middle_Vx	x						x		x	
left_middle_Vy	x						x		x	
left_middle_Vz	x						x		x	
left_ring_Vx	x						x		x	
left_ring_Vy	x						x		x	
left_ring_Vz	x						x		x	
left_thumb_Vx	x		x		x		x		x	
left_thumb_Vy	x		x		x		x		x	
left_thumb_Vz	x		x		x		x		x	
left_pinky_Vx	x						x		x	
left_pinky_Vy	x						x		x	

left_pinky_Vz	x			x	x
right_index_Vx	x			x	x
right_index_Vy	x			x	x
right_index_Vz	x			x	x
right_middle_Vx	x			x	x
right_middle_Vy	x			x	x
right_middle_Vz	x			x	x
right_ring_Vx	x			x	x
right_ring_Vy	x			x	x
right_ring_Vz	x			x	x
right_thumb_Vx	x	x	x	x	x
right_thumb_Vy	x	x	x	x	x
right_thumb_Vz	x	x	x	x	x
right_pinky_Vx	x			x	x
right_pinky_Vy	x			x	x
right_pinky_Vz	x			x	x

Annex F: Tables extracted from analysis tool

The variables used in the tables are explained here below:

<table>
<tr><th colspan="2">TABLE 1: MOVEMENT</th></tr>
<tr><td colspan="2">Fingers movement amplitude</td></tr>
<tr><td>maxdifLIx, maxdifLIz, maxdifLMx,maxdifLMz, maxdifLRx, maxdifLRz, maxdifLTx, maxdifLTz, maxdifLPx, maxdifLPz, maxdifLIy,maxdifLMy,maxdifLRy, maxdifLTy, maxdifLPy, maxdifIx,maxdifIz, maxdifMx, maxdifMz, maxdifRx, maxdifRz, maxdifTx, maxdifTz, maxdifPx, maxdifPz, maxdifIy, maxdifMy, maxdifRy, maxdifTy,maxdifPy</td><td>These variables show the difference between the minimum and maximum point in space for each hand (L/R), for each finger (index (I), middle (M), thumb (T), ring (R) and pinky (P)) on each direction (x,y,z).

This provides information about the amplitude of the movement of each finger.

In the case of those exercises done on the horizontal plane (XZ), the amplitude of movement in Y is a measure of instability. These exercises are: 1-4.

In the case of the exercises where the fingers move on the vertical plane (YZ), the instability is measured with the amplitude along X. These exercises are 5-8.

The exercises that measure thumb function alone (3-6), only have the variables for this finger. The rest of exercises uses all of them.</td></tr>
<tr><td colspan="2">Hand center movement amplitude</td></tr>
<tr><td>maxdifRHCx,maxdifRHCy,maxdifRHCz, maxdifLHCx, maxdifLHCy, maxdifLHCz</td><td>These variables show the difference between the minimum and maximum point in space for each hand's center (L/R) along each direction (x,y,z).

This provides information about the movement of the hand's center, which for exercises 1-8, where the hand is supposed to be kept stable, is a measure of instability.

In the case of exercises 9-10, these variables are used to follow hand center's movement.</td></tr>
<tr><td colspan="2">Distance between fingers</td></tr>
<tr><td>maxLdPR, maxLdRM, maxLdMI, maxLdIT, maxLdPT, maxRdPR,maxRdRM,maxRdMI, maxRdIT, maxRdPT</td><td>These variables measure the maximum distance between finger's tips of adjacent fingers for each hand (L/R). It measures pinky-ring (PR), ring-middle (RM), middle-index (MI), index-thumb (IT) and pinky-thumb (PT). This last one is a measurement of total aperture of the hand.</td></tr>
<tr><th colspan="2">TABLE 2: SPEED</th></tr>
<tr><td colspan="2">Maximum finger speeds reached</td></tr>
</table>

maxLVIx, maxLVMx, maxLVRx, maxLVTx, maxLVPx, maxLVIy, maxLVMy, maxLVRy, maxLVTy, maxLVPy, maxLVIz, maxLVMz, maxLVRz, maxLVTz, maxLVPz, maxRVIx, maxRVMx, maxRVRx, maxRVTx, maxRVPx, maxRVIy, maxRVMy, maxRVRy, maxRVTy, maxRVPy, maxRVIz, maxRVMz, maxRVRz, maxRVTz,maxRVPz	These variables save the maximum absolute speed reached by each finger (I, R, M, T, P) of each hand (L/R) on each direction (x,y,z). It is a measure of finger's power and capacity to perform the movement.
Maximum and minimum hand center speeds reached	
maxLHVx, minLHVx, maxLHVy , minLHVy ,maxLHVz, minLHVz, maxRHVx, minRHVx, maxRHVy, minRHVy, maxRHVz, minRHVz	These variables show maximum and minimum speeds reached by each hand center (L/R). In this case, there is no absolute value, and the both the minimum and maximum show the maximum speed reached, one in each sense. They provide this speed along each direction (x,y,z). These variables are only used for exercises 9 and 10, since they are the only ones where the hand center is supposed to move.
TABLE 3: ANGLES	
Yaw	
meanLYaw, maxLYaw, minLYaw, meanRYaw, maxRYaw, minRYaw,	Minimum, maximum and mean values of yaw angle for each hand (L/R).
Pitch	
meanLPitch, maxLPitch, minLPitch, meanRPitch, maxRPitch, minRPitch	Minimum, maximum and mean values of pitch angle for each hand (L/R).
Roll	
meanLRoll, maxLRoll, minLRoll, meanRRoll, maxRRoll, minRRoll	Minimum, maximum and mean values of roll angle for each hand (L/R).

Table 8. Explanation of all the used variables

EX1. TABLES

MOVEMENT

t1	maxdifLIx	maxdifLIz	maxdifLMx	maxdifLMz	maxdifLRx
6,209252	72,40676	140,93368	62,229006	124,84513	55,32752
maxdifLRz	**maxdifLTx**	**maxdifLTz**	**maxdifLPx**	**maxdifLPz**	**maxdifLIy**
157,91458	78,75216	109,09071	68,47384	124,899	212,08857
maxdifLMy	**maxdifLRy**	**maxdifLTy**	**maxdifLPy**	**maxdifLHCx**	**maxdifLHCy**

206,6353	214,34346	220,12156	224,42206	42,22379	242,5962
maxdifLHCz	maxLdPR	maxLdRM	maxLdMI	maxLdIT	maxLdPT
242,5962	47,35898	30,59375	40,67932	64,22556	168,92267

SPEED

maxLVIx	maxLVMx	maxLVRx	maxLVTx	maxLVPx	maxLVIy	maxLVMy	maxLVRy
566,4717	294,5278	339,5214	1039,302	293,1691	1023,175	1272,599	1253,283
maxLVTy	maxLVPy	maxLVIz	maxLVMz	maxLVRz	maxLVTz	maxLVPz	
276,0571	930,1824	810,4786	964,7543	938,9692	1163,073	854,307	

ANGLES

meanLPitch	meanLYaw	meanLRoll	minLPitch	minLYaw
-0,0178204	-0,10099	0,01154294	-0,4033065	-0,5708138
minLRoll	maxLPitch	maxLYaw	maxLRoll	
-0,2344262	0,5949344	0,05494716	0,1924727	

EX2. TABLES

MOVEMENT

t2	maxdifIx	maxdifIz	maxdifMx	maxdifMz	maxdifRx
6,209252	69,88839	160,23048	74,55112	181,9384	74,49242
maxdifRz	maxdifTx	maxdifTz	maxdifPx	maxdifPz	maxdifIy
174,44842	51,1312	85,017061	98,802356	141,43499	57,8939
maxdifMy	maxdifRy	maxdifTy	maxdifPy	maxdifRHCx	maxdifRHCy
71,6957	56,3746	109,2142	48,0197	158,38659	55,3429
maxdifRHCz	maxRdPR	maxRdRM	maxRdMI	maxRdIT	maxRdPT
55,3429	43,123974	31,76048	46,98152	87,65744	156,293299

SPEED

maxRVIx	maxRVMx	maxRVRx	maxRVTx	maxRVPx	maxRVIy	maxRVMy	maxRVRy
270,3069	318,6985	379,6521	268,6899	436,1769	1174,705	1188,763	899,0895
maxRVTy	maxRVPy	maxRVIz	maxRVMz	maxRVRz	maxRVTz	maxRVPz	
461,8455	809,9252	1305,508	1316,042	967,1907	329,6817	705,6935	

ANGLES

meanRPitch	meanRYaw	meanRRoll	minRPitch	minRYaw
-0,0535634	-0,1155021	-0,1264032	-0,2009892	-0,2679595
minRRoll	maxRPitch	maxRYaw	maxRRoll	
-0,4517866	0,1568919	0,1081812	0,05927758	

EX3. TABLES

MOVEMENT

t3	maxdifLTx	maxdifLTz	maxdifLTy	maxdifLHCx	maxdifLHCy	maxdifLHCz
5,378259	88,643863	124,51641	205,86087	24,613672	225,14839	225,14839

SPEED

maxLVTx	maxLVTy	maxLVTz
370,8887	305,7482	317,9807

ANGLES

meanLPitch	meanLYaw	meanLRoll	minLPitch	minLYaw
-0,0627244	-0,2030488	0,0823722	-0,4265542	-0,637039
minLRoll	**maxLPitch**	**maxLYaw**	**maxLRoll**	
-0,2252937	0,4958103	-0,0036653	0,3797153	

EX4. TABLES

MOVEMENT

t4	maxdifRTx	maxdifRTz	maxdifRTy	maxdifRHCx	maxdifRHCy	maxdifRHCz
5,378259	53,52392	116,91088	129,4084	51,78059	55,5865	55,5865

SPEED

maxRVTx	maxRVTy	maxRVTz
343,4955	367,9441	515,8249

ANGLES

meanRPitch	meanRYaw	meanRRoll	minRPitch	minRYaw
-0,008327	-0,0957484	-0,1253394	-0,2044841	-0,2599737
minRRoll	**maxRPitch**	**maxRYaw**	**maxRRoll**	
-0,4517866	0,2771231	0,05232032	0,1135479	

EX5. TABLES

MOVEMENT

t5	maxdifLTy	maxdifLTz	maxdifLTx	maxdifLHCx	maxdifLHCy	maxdifLHCz
4,960383	184,16231	96,6956	79,79222	41,801893	214,1138	214,1138

SPEED

maxLVTx	maxLVTy	maxLVTz
370,8887	305,7482	317,9807

ANGLES

meanLPitch	meanLYaw	meanLRoll	minLPitch	minLYaw
0,03331559	-0,1696728	0,09014663	-0,3383557	-0,637039
minLRoll	**maxLPitch**	**maxLYaw**	**maxLRoll**	
-0,1615687	0,3770233	0,2328631	0,3797153	

EX6. TABLES

MOVEMENT

t6	maxdifRTy	maxdifRTz	maxdifRTx	maxdifRHCx	maxdifRHCy	maxdifRHCz
4,960383	90,6803	115,47251	36,90484	51,78059	55,5865	55,5865

SPEED

maxRVTx	maxRVTy	maxRVTz
343,4955	367,9441	515,8249

ANGLES

meanRPitch	meanRYaw	meanRRoll	minRPitch	minRYaw
-0,0550843	-0,023116	-0,1180153	-0,172652	-0,1496251
minRRoll	**maxRPitch**	**maxRYaw**	**maxRRoll**	
-0,3561779	0,1699656	0,108283	-0,0049521	

EX7. TABLES

MOVEMENT

t7	maxdifLIy	maxdifLMy	maxdifLRy	maxdifLTy	maxdifLPy
5,185706	206,01769	195,79818	194,4672	212,59191	206,23083
maxdifLIz	**maxdifLMz**	**maxdifLRz**	**maxdifLTz**	**maxdifLPz**	**maxdifLIx**
163,90016	147,16117	163,93283	117,9417	138,17496	70,08396
maxdifLMx	**maxdifLRx**	**maxdifLTx**	**maxdifLPx**	**maxdifLHCx**	**maxdifLHCy**
72,715299	72,431306	85,55001	70,31354	40,823851	215,99705
maxdifLHCz	**maxLdPR**	**maxLdRM**	**maxLdMI**	**maxLdIT**	**maxLdPT**
215,99705	32,87584	19,940834	51,49057	63,3722	119,52188

SPEED

maxLVIx	maxLVTx	maxLVIy	maxLVTy	maxLVIz	maxLVTz
495,375	537,6537	796,2106	229,1277	1155,773	406,6443

ANGLES

meanLPitch	meanLYaw	meanLRoll	minLPitch	minLYaw
-0,2916684	0,030899	-0,0005609	-0,6161873	-0,3326604
minLRoll	**maxLPitch**	**maxLYaw**	**maxLRoll**	
-0,2982724	0,3892262	0,2328631	0,2404155	

EX8. TABLES

MOVEMENT

t8	maxdifIy	maxdifMy	maxdifRy	maxdifTy	maxdifPy
5,185706	103,3024	88,4836	74,751	150,873	55,2202
maxdifIz	**maxdifMz**	**maxdifRz**	**maxdifTz**	**maxdifPz**	**maxdifIx**
166,97841	185,35139	172,71625	151,480065	181,29323	70,96754
maxdifMx	**maxdifRx**	**maxdifTx**	**maxdifPx**	**maxdifRHCx**	**maxdifRHCy**
70,69479	73,61804	83,60169	73,938903	57,24056	56,9009
maxdifRHCz	**maxRdPR**	**maxRdRM**	**maxRdMI**	**maxRdIT**	**maxRdPT**
56,9009	23,859	18,01707	38,90042	87,65744	123,877441

SPEED

maxRVIx	maxRVTx	maxRVIy	maxRVTy	maxRVIz	maxRVTz
316,8958	332,2211	1026,256	475,9747	1144,811	457,2042

ANGLES

meanRPitch	meanRYaw	meanRRoll	minRPitch	minRYaw
-0,3481067	0,01628635	-0,1108636	-0,7244865	-0,4735377
minRRoll	**maxRPitch**	**maxRYaw**	**maxRRoll**	
-0,5534034	0,3007304	0,2298823	0,03205266	

EX9. TABLES

MOVEMENT

t9	maxdifLHCx	maxdifLHCy	maxdifLHCz
16,3381	165,49091	95,0962	95,0962

SPEED

maxLHVx	minLHVx	maxLHVy	minLHVy	maxLHVz	minLHVz
610,4728	-318,108	222,3571	-618,2849	222,3571	-618,2849

ANGLES

meanLPitch	meanLYaw	meanLRoll	minLPitch	minLYaw
0,40407137	-0,1112186	0,19445759	-1,358287	-1,430864
minLRoll	**maxLPitch**	**maxLYaw**	**maxLRoll**	
-0,9419718	1,953549	3,017393	2,893242	

EX10. TABLES

MOVEMENT

t10	maxdifRHCx	maxdifRHCy	maxdifRHCz
16,3381	158,38659	55,3429	55,3429

SPEED

maxRHVx	minRHVx	maxRHVy	minRHVy	maxRHVz	minRHVz
292,9933	-406,991	218,7705	-360,2917	218,7705	-360,2917

ANGLES

meanRPitch	meanRYaw	meanRRoll	minRPitch	minRYaw
0,21264003	0,23934277	0,08050251	-0,4361286	-0,1118006
minRRoll	**maxRPitch**	**maxRYaw**	**maxRRoll**	
-0,4489671	0,7873281	0,7873535	1,151773	