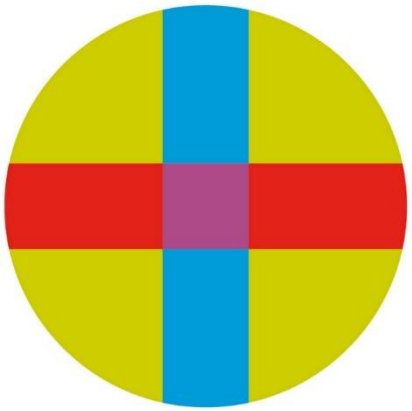
UNIVERSITY CEU - SAN PABLO

POLYTECHNIC SCHOOL

BIOMEDICAL ENGINEERING MASTER



MASTER THESIS

VALIDATION OF A TOOL FOR COMPUTATIONAL ASSESSMENT OF UPPER LIMB MOVEMENT IN PATIENTS WITH STROKE

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ABSTRACT

Deficits affecting hand motor skills negatively impact in the functionality and quality of life of stroke patients. In practice, these deficits are assessed with clinical scales that are not sufficiently accurate. It is therefore necessary to develop tools that allow to set an objective assessment to better establish the degree of disability.

The purpose of this MSc thesis is the validation of a minimally invasive computational tool, based on a virtual reality environment that captures kinematic data from hand movement tracking through a portable device which incorporates two cameras and three infrared sensors (Leap Motion ®).

Eighty stroke patients and ninety-three controls were recruited. The software allowed identification of significant differences in motor performance between patients´ symptomatic hand and controls and also between patients´ theoretically unaffected side and controls ($p < 0.05$). Moreover, correlations between kinematic data and clinical scales scores were poor (Pearson's coefficient: 0.15 to 0.48), which suggests that the application enables measurement of deficits that are not detected by the clinical scales.

This software for kinematic analysis using optical technology provides, therefore, a useful tool to objectify hand deficits after a stroke. It may aid in the accurate assessment of disability and in the optimization of rehabilitation therapies.

RESUMEN

Los déficits que afectan a la motricidad de la mano tienen un impacto negativo en la funcionalidad y la calidad de vida de los pacientes con ictus. En la práctica, estos déficits se evalúan con escalas clínicas que no son suficientemente precisas. Por ello, es necesario desarrollar herramientas que permitan una evaluación objetiva para establecer mejor el grado de discapacidad.

El objetivo de este trabajo de fin de máster es, la validación de una herramienta computacional mínimamente invasiva basada en un entorno de realidad virtual que captura datos cinemáticos de seguimiento del movimiento de la mano a través de un dispositivo portátil que incorpora dos cámaras y tres sensores infrarrojos (Leap Motion ®).

Se reclutaron ochenta pacientes con ictus y noventa y tres controles. El software permitió identificar diferencias significativas en el rendimiento motor entre la mano sintomática de los pacientes y los controles y también entre el lado teóricamente no afectado de los pacientes y los controles ($p < 0,05$). Además, las correlaciones entre los datos cinemáticos y la puntuación de las escalas clínicas fueron pobres (coeficiente de Pearson: 0,15 a 0,48), lo que sugiere que la aplicación permite medir déficits que no son detectados por las escalas clínicas.

Este software de análisis cinemático mediante tecnología óptica proporciona, por tanto, una herramienta útil para objetivar los déficits de la mano tras un ictus. Pudiendo ayudar a la evaluación precisa de la discapacidad y a la optimización de las terapias de rehabilitación.

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1 INTRODUCTION

1.1 Scope and aims

Stroke is the second leading cause of death worldwide and the leading cause of disability [1]. It is estimated that 25% of the world's population is at risk of suffering a stroke during their lifetime [2]. According to data obtained from the Spanish society of neurology, around 110.000 people suffer a stroke every year, and a large percentage of them will suffer from mobility deficits in the upper limb that negatively impact their activities of daily living and their quality of life [3]. It is therefore important to adequately assess the hand deficit in order to establish individualized rehabilitation programmes that allow the patient to restore functionality, as this is not adequately achieved with the available clinical scales.

With this MSc thesis, the validation of a minimally invasive computational tool is intended, with the aim of parameterizing the kinematic data to quantify it and measure the movement objectively.

A system that allows objective and accurate assessment of the upper limb movement by means of optical capture is proposed. Based on its design, it could be incorporated in rehabilitation programs based on self-administered virtual reality both in the hospital and at home.

To this end, two study phases will be carried out:

- Case – Control Study to check if the tool is able to discriminate the deficit against healthy subjects. This will include the conformation of a complete and robust database with the clinical data of the patients, the kinematic parameters to be analyzed (previously selected and preprocessed) and the subsequent processing of the data through statistical analysis.

- Longitudinal Study to find out if the tool can discriminate the evolution of patients through statistical analysis between baseline and follow-up data.

The validation of this tool would help the neurologist in the diagnosis process. Moreover, it will bring the possibility for patients with hand movement deficits to have a system that keeps track of their evolution while being used as a rehabilitation tool and it will allow to check the response to the different recovery treatments, individualizing them.

Furthermore, software developments and usage functionalities to assist neurologists in the diagnostic process will be added. Including an automated reporting system that shows the deficit of each parameter to be analyzed and a new, more intuitive interface with new functionalities, such as: a new method to identify the user, different ways to navigate through screens and an automated approach to assure that the exercise is correctly performed eliminating subjectivity in the trial.

1.2 Thesis Structure

This MSc Thesis has been structured as shown in Figure 1:

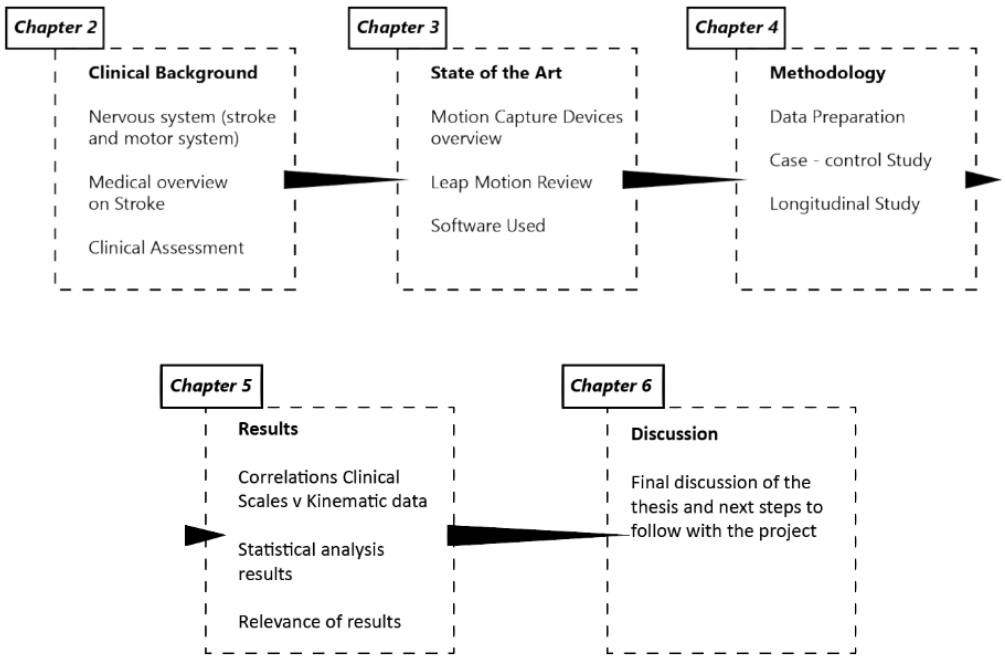


Figure 1 Graphical structure of the MSc Thesis

- **Chapter 2**. Clinical background. In this chapter, a review of the clinical aspects involved in this MSc thesis is performed. The basic elements of the nervous system and the areas of the brain involved in the control of movement are explained, with special emphasis on the upper limb. Then, a general review of stroke, including: classification, prognosis rehabilitation and assessment is carried out.

- **Chapter 3**. State of the Art. This chapter is divided in two parts: A review of the available motion capture sensors and how they are applied in different studies and the explanation of the tool used and proposed to capture kinematic data.

- **Chapter 4**. Methodology. All of the methods employed in the validation of the tool are described in this chapter. The design of the different studies carried out, the conformation of the database, and the selection of the different parameters to be studied as well as their processing, among other issues, are detailed here. This chapter includes an explanation of the modifications made to the initial tool. This includes changes to the interface, new functionalities such as the introduction of an automated results report or a new method of storing data.

- **Chapter 5**. Results. The results obtained in each of the studies are presented and discussed in this chapter.

- **Chapter 6**. Discussion. This chapter serves as the closure of the thesis where the conclusions and future directions are presented.

2 CLINICAL BACKGROUND

2.1 Nervous System

2.1.1 ELEMENTS OF THE NERVOUS SYSTEM

The nervous system is made up of excitable cells called neurons, which specialize in processing and transmitting information. They interact with each other at junctions called synapses, where information is transferred from one neuron to the next [4], it is at these contacts that the nerve impulse is transmitted.

In general terms, the nervous system can be divided into Central Nervous System (CNS) which includes cerebrum, cerebellum, brain stem and spinal cord and the Peripheral Nervous System (PNS) which consists of the spinal nerves and peripheral nerves.

The transmission of information through the nervous system can be explained in three steps (See Figure 2): i) A stimulus acting on the sense organs generates a nerve impulse which is transmitted to the CNS (afferent impulse), ii) a phase of complex processing of these impulses takes place in the central nervous system (information processing), iii) the CNS generates new impulses that travel towards the PNS (efferent impulses) that will result in a response to the previous impulse [4].

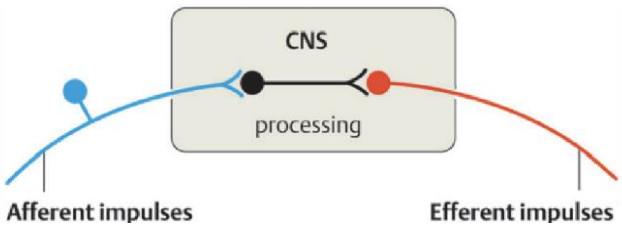


Figure 2 Information flow in the nervous system schema [4].

The information is transferred from one neuron to the next by chemicals called neurotransmitters. It is important to know that neurons transmit information in only one direction, as they are bipolar, this means that they receive information at one point of the neuron (dendrite) and transmit it from the opposite point (axon) (See Figure 3) [5].

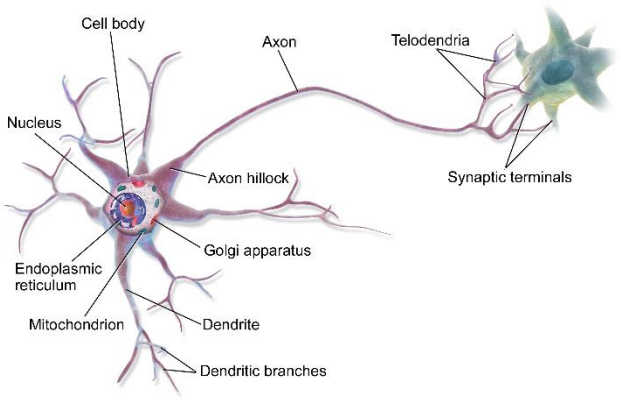
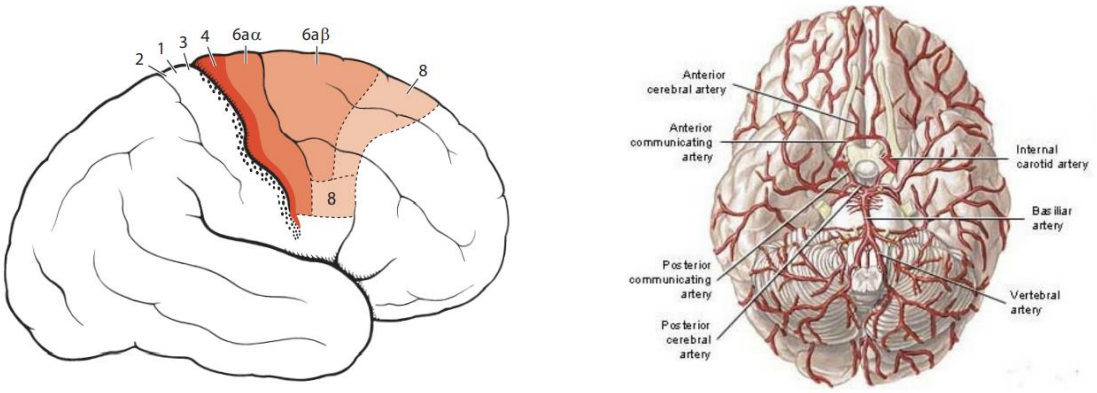


Figure 3 Structure of a neuron [5].

2.1.2 STROKE AND MOTOR SYSTEM

It is important to be aware of which part of the brain is responsible for each of the functions, as depending on where the lesion is located, the patient will present different symptoms. The area responsible for generating the motor impulses that lead to voluntary movement is the primary motor cortex known as the Brodmann Area 4 (See Figure 4 a) [4] [6]. The middle cerebral artery (a branch of the internal carotid artery) is responsible for the irrigation of almost the entire lateral surface of the cerebral hemispheres (See Figure 4 b) , including the portion of the primary motor and sensory cortex. Therefore, lesions in this territory are susceptible to cause movement deficits in the upper limb [7].



a) b)

Figure 4 a) Brodmann areas responsible for motor impulses [4] b) Cerebral artery Irrigation [6].

The process of generating voluntary movement involves the first motoneuron which transmits the information through the long fiber pathways (Corticonuclear tract/ Corticospinal or Pyramidal tract), to the nucleus of the cranial nerves in the brainstem and to the anterior horn in the spinal cord. It makes synaptic contact with the second motoneuron, that generates new impulses to the peripheral nerves ending in the skeletal muscles to produce the movement [8].

As shown in the schematic representation of motor pathways (See Figure 5), fibers in the pyramidal tract cross the midline at different points in the brainstem and make synapsis with the second motoneuron in the contralateral side. That is why the motor deficit of a patient with a stroke is typically shown on the side contralateral to the lesion. At the spinal cord this fiber pathway is located at the lateral corticospinal tract.

However, there is a portion of corticospinal fibers that do not decussate and descend ipsilaterally in the anterior corticospinal tract, being responsible of certain degree of ipsilateral motor activation.

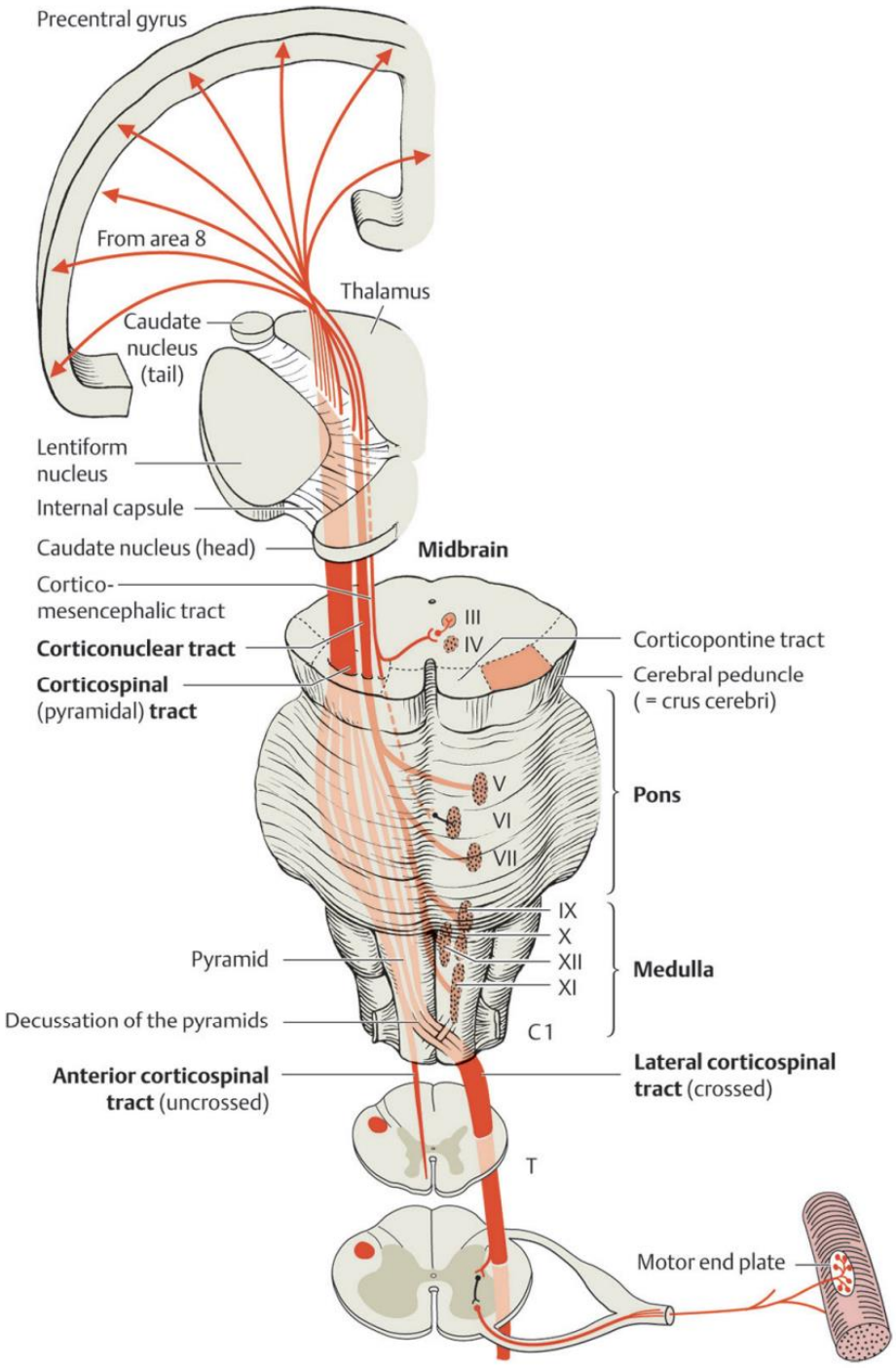


Figure 5 Course of the pyramidal tract [4].

2.2 Cerebrovascular Diseases

The term cerebrovascular disease or stroke refers to an acute cerebral circulatory disorder that results in a temporary or permanent impairment of one or more parts of the brain.

Stroke is a major health problem as it is the second cause of mortality worldwide, and the first of acquired disability in adults [1]. The estimated cost of stroke is over 721 billion USD, which implies 0,66% of the global GDP [9]. But the real concern about stroke is that the absolute number of cases has increased substantially in the last two decades: 70% increase in the number of cases, 40% in deaths due to stroke and 143% in disability-adjusted life-years lost [9], with the largest part of the world's stroke burden residing in lower-income countries. Moreover the prevalence of stroke is expected to increase by 35% in 2035 due to the increased life-expectancy. This calls for the development of accessible tools that helps improve allow the recovery of those patients who have suffered a stroke.

2.2.1 STROKE CLASIFICATION

There are different types of strokes which are classified according to the nature of the lesion into two main groups [10]: ischemic stroke and hemorrhagic stroke, which in turn are subdivided according to the etiology and location of the lesion, as shown in

Figure 6:

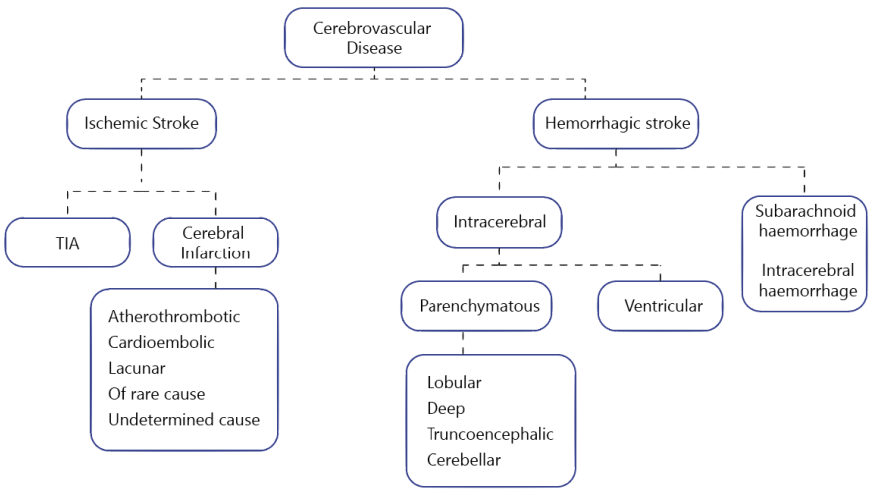


Figure 6 Cerebrovascular Diseases Classification [10]

Ischemic Stroke

It is defined as a regional decrease of cerebral blood flow below energy requirements, due to occlusion of a cerebral artery resulting in transient or persistent focal neurological deficits. Ischemic strokes represent between 80 and 85 percent of all strokes and they can be divided into TIA and Cerebral Infarction [11] [12].

Transient Ischemic Attack (TIA)

TIA is defined as a brief episode of focal cerebral ischemia, resulting in reversible focal neurological deficit, of short duration, always less than 24h (usually minutes) and without evidence of cerebral infarction on neuroimaging tests [10].

TIA patients are considered as a high-risk group for stroke and other vascular events. That is why once diagnosed, investigation should be directed towards identifying the causative mechanism [10].

Cerebral infarction

This is defined by the presence of an irreversible brain damage caused by qualitative or quantitative impairment of the circulatory supply to an encephalic territory, resulting in tissue necrosis that leads to a established neurological deficit [10].

According to the etiology, cerebral infarction can be classified into groups [10] [13]:

- *Atherothrombotic infarction:* infarction caused by atherosclerosis of a large or medium-sized artery.
- *Cardioembolic infarction:* infarction caused by an embolic heart disease. The most common is atrial fibrillation although there are many other causes (valvulopathy, mainly mitral stenosis, prosthetic valves, acute myocardial infarction, intracardiac thrombus or tumor, endocarditis, etc.).
- *Lacunar infarction:* small sized infarction (<1,5 cm of diameter) caused by small vessel occlusion, i.e. perforating arteries arteriolosclerosis.

- *Cerebral infarction of uncommon cause:* Infarction of other known causes when atherothrombotic, cardioembolic or lacunar origin has been discarded (e.g.: arterial dissection, neoplastic disease, prothrombotic states…).

- *Cerebral infarction of undetermined cause due to coexistence of causes:* (any of the abovementioned).

- *Cryptogenic cerebral infarction:* Cerebral infarction without any determined cause after an exhaustive diagnostic study.

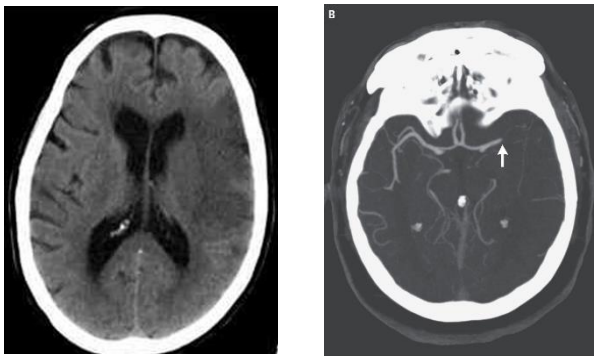


Figure 7 Ischemic Stroke Images [12].

Hemorrhagic Stroke

Hemorrhagic stroke represents about 15-20 % of incident stroke cases. However, it associates a worse prognosis, with higher rates of morbidity and mortality [14].

Hemorrhagic stroke is defined as an intracranial bleeding caused by a non-traumatic vascular rupture and is divided into two groups according to the location.

Intracerebral hemorrhages

Intracerebral hemorrhage occurs when the blood spillage takes place inside the brain. The most frequent cause is chronic high blood pressure. Intracerebral hemorrhage represents about 10% of all strokes [15].

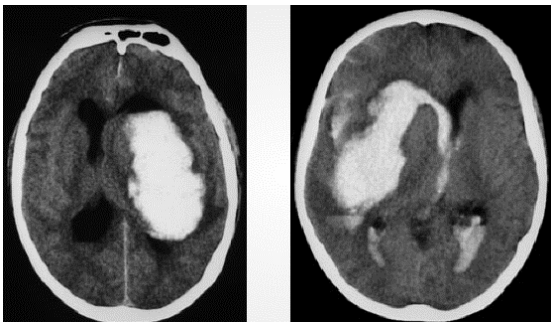


Figure 8 Intracerebral hemorrhage [13].

Subarachnoid hemorrhage

A subarachnoid hemorrhage is a bleeding into the space between the inner layer (pia mater) and the middle layer (arachnoid) of the tissue covering the brain (subarachnoid space) [10].

Subarachnoid hemorrhage is considered a stroke only when it occurs spontaneously, i.e. when the hemorrhage is not the result of external forces, such as traumatism. A spontaneous subarachnoid hemorrhage usually results from the sudden rupture of an aneurysm in a cerebral artery.

About 35% of people with subarachnoid hemorrhage from a ruptured aneurysm die before reaching hospital. Another 15% die within a few weeks because of rebleeding and this is why early diagnosis and treatment of the aneurysm is key [10] [15].

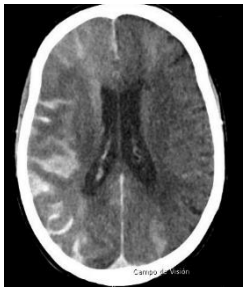


Figure 9 Subarachnoid hemorrhage [13].

2.2.2 STROKE DIAGNOSIS AND TREATMENT

Stroke is a medical emergency. Brain damage progresses very rapidly after stroke onset and therefore, it is important to urgently identify and treat stroke in order to reduce irreversible brain damage and achieve a better functional recovery of the patient [16].

The emergency diagnosis includes the identification of the subtype of stroke by appropriate clinical examination and neuroimaging to promptly indicate the specific treatment according to the diagnosis and patient´s condition (for example intravenous thrombolysis or mechanical thrombectomy for candidate patients with ischemic stroke). Specialized stroke care in stroke units has demonstrated to improve outcomes. Also, an exhaustive study to establish the etiology is mandatory in order to implement the most adequate preventive treatment to avoid recurrences. Finally, a proper evaluation of the sequelae is also needed to indicate the most appropriate rehabilitation therapies [16].

The neurorehabilitation process is intended to prevent deficit-related complications or worsening during the acute phase and in the long term, to reduce the neurological deficit suffered after a stroke, in order to achieve the maximum possible functional capacity. [17]. There is evidence, that biological repair processes do actually exit after a stroke and that a certain degree of brain plasticity occurs to improve recovery. This can be enhanced by rehabilitation therapies [18]. Timing in this phase is also crucial. The neurorehabilitation process should begin once the patient is clinically stable, as there is evidence that there are periods of time in which the patient improves in a more optimal way and is able to recover functionalities due to the plasticity of the brain [19] [20] [21].

In this process, physiotherapists, occupational therapists, doctors and nowadays engineers must work together in order to design individualised therapies for each patient, keeping an objective control of the progress in order to reduce the deficit as much as possible.

The presence of engineers in the field of neurorehabilitation is becoming increasingly important with the development of new technologies. More specifically, they will be in charge of linking all these technological advances with the health field,

providing clinicians with the tools to diagnose, prevent, cure and control, in this case, neurological diseases. The importance of engineering applied to medicine lies precisely in finding ways to improve the quality of life of human beings through the design and creation of devices and any other technical solutions that help the doctor to provide better patient care, diagnosis and treatment.

Research in biomedical technologies through multidisciplinary teams is essential for the future development of neurorehabilitation services by facilitating the personalisation of treatments, modulating the intensity and duration of programmes, monitoring in real and deferred time, allowing closer follow-up and updating the current clinical scales to assess damage more objectively.

2.2.3 CLINICAL SCALES FOR ASSESSMENT OF FUNCTIONAL DEFICITS AFTER A STROKE

Clinical examination is essential to assess the consequences of the stroke, to establish which functions are affected and to detect evolutionary changes. The quantification of these deficits is done with clinical scales, which parameterize these deficits, making it possible to establish the severity in the acute phase and to measure the evolutionary changes. Moreover, they serve to establish a common language among clinicians exploring the patient. Within the field of neurological damage there are different scales that assess different aspects: neurological deficit (NIHSS, Fugl-Meyer Assessment) [22] [23], impact on activities of daily living (modified Rankin Scale (mRS) or Barthel Index [24], quality of life (EuroQol 5D) [25] or cognitive deficit. Each of them has its own level of complexity, being more general or more specific, depending on the final objective to be achieved.

Clinical scales are, therefore, tools that allow us to assess the patient's condition objectively and help us to make decisions on both diagnosis and treatment. However, although these scales are validated and reproducible, they always depend to a greater or lesser extent on the subjectivity of the assessor, which poses major problems when assessing mild impairments, making them much less discriminating in this situation. This is particularly noticeable in the assessment of hand deficits for which the scales are either not sufficiently discriminating or are too cumbersome for everyday use.

These scales should be applied at the time of the patient's admission and according to established time periods.The most widely used and accepted clinical scales for assessing neurological deficit after stroke and which will be of interest for the development of this thesis are detailed below.

NATIONAL INSTITUTE OF HEALTH STROKE SCALE (NIHSS)

The NIHSS (National Institute of Health Stroke Scale) [22] is the most commonly used scale for the assessment of neurological deficits in stroke patients, both at the onset and during its evolution.

It is made up by 11 items that allow a quick and standardized exploration and include assessment of the level of consciousness, visual disturbances, oculomotor function, facial palsy, motor function, sensibility, coordination, language and neglect. The scale has a score ranging from 0 to 42 with higher scores indicating greater severity of deficit. It also allows to detect neurological improvement or deterioration (establishing for these cases a difference of at least 4 points with respect to the baseline score) [22] [26] [27]. According to the score obtained the severity of the neurological deficit can be classified as: no deficit: 0; minor deficit: 1-4; moderate deficit: 5-15; moderate to severe deficit: 16-20; severe > 20.

The scale has some limitations, as for example, infarcts occurring in the dominant (usually left) MCA territory will score higher than those occurring on the right side, as language disturbances score higher than other items in the scale and it underscores the affectation of the vertebro-basilar territory. [28]

Furthermore, it does not directly assess hand function which prevents the scale from detecting minor changes in patient´s evolution. [29].

The NIHSS is summarized in Figure 10.

1.a. Level of Consciousness	Alert Drowsy Stuporous Coma	0 1 2 3	
1.b. LOC Questions	Answers both correctly Answers one correctly Incorrect	0 1 2	
1.c. LOC Commands	Obeys both correctly Obeys one correctly Incorrect	0 1 2	
2. Pupillary Response	Both reactive One reactive Neither reactive	0 1 2	
3. Best Gaze	Normal Partial gaze palsy Forced deviation	0 1 2	
4. Best Visual	No visual loss Partial hemianopia Complete hemianopia	0 1 2	
5. Facial Palsy	Normal Minor Partial Complete	0 1 2 3	
6. Best Motor Arm	No drift Drift Can't resist gravity No effort against gravity	0 1 2 3	
7. Best Motor Leg	No drift Drift Can't resist gravity No effort against gravity	0 1 2 3	
8. Plantar Reflex	Normal Equivocal Extensor Bilateral extensor	0 1 2 3	
9. Limb Ataxia	Absent Present in upper or lower Present in both	0 1 2	
10. Sensory	Normal Partial loss Dense loss	0 1 2	
11. Neglect	No neglect Partial neglect Complete neglect	0 1 2	
12. Dysarthria	Normal articulation Mild to moderate dysarthria Near unintelligible or worse	0 1 2	
13. Best Language	No aphasia Mild to moderate aphasia Severe aphasia Mute	0 1 2 3	
14. Change from Previous Exam	Same Better Worse	S B W	
15. Change from Baseline	Same Better Worse	S B W	

Figure 10. NIH Stroke scale [22]. For questions 6 and 7, both sides should be assessed separately.

FUGL MEYER ASSESSMENT (FMA-UE)

Fugl-Meyer Assessment (FMA) scale is an index to assess the sensorimotor impairment in individuals who have had stroke. This scale arises from the need to present a cumulative numerical score capable of describing and assessing [23] [30].

The Fugl Meyer scale has five domains (motor function, balance, sensation, range of motion and joint pain), covering the three dimensions of stroke functional status, with 113 items in total. Due to its complexity, it is possible to divide it into sections (A-C. Upper extremity, D. coordination/speed upper extremity, E. Lower extremity, F. coordination/speed lower extremity, G. Balance, H. Sensation, I. Post Stroke hemiplegia, J. Joint motion / Motion pain)

Section C (see Table 1) assesses the movement and strength of the hand in seven items divided into two main groups: mass flexion and extension of the hand and a group of five classes of grasps with different types of muscular co-contractions. Each item is evaluated with a number between 0 and 2, where 0 is associated with the impossibility of performing the task and 2 when the task is performed without any problem, giving a maximum score of 14 points for a theoretically unaffected hand.

FMA-UE scale has some limitations in assessing precise movements in patients that may affect activities of daily living.

FUGL MEYER ASSESSMENT (FMA-UE)

C. HAND Support may be provided at the elbow to keep 90° flexion, no support at the wrist, compare with unaffected hand, the objects are interposed, active grasp

		None	Partial	Full
Mass Flexion from full active or passive extension		0	1	2
Mass Extension from full active or passive flexion		0	1	2
GRASP				
a. Hook Grasp flexion in PIP and DIP (digits II-V), extension in MCP II-V	Cannot be performed Can hold position but weak Mantains position against resistance	0	1	2
b. Thumb Adduction 1-st CMC, MCP, IP at 0°, scrap of paper between thumb and 2-nd MCP joint	Cannot be performed Can hold paper but not against tug Can hold paper against a tug	0	1	2
c. Pincer grasp, opposition pulpa of the thumb against the pulpa of 2-nd finger, pencil, tug upward	Cannot be performed Can hold pencil but not against tug Can hold pencil against a tug	0	1	2
d. Cylinder grasp cylinder shaped object (small can) tug upward, opposition of thumb and fingers	Cannot be performed Can hold cylinder but not against tug Can hold cylinder against a tug	0	1	2
e. Espherical grasp fingers in abduction/flexion, thumb opposed, tennis ball, tug away	Cannot be performed Can hold ball but not against tug Can hold ball against a tug	0	1	2

Table 1. FMA-UE Clinical Scale.

In addition to the scales responsible for measuring the deficit after neurological damage, the most relevant scales for assessing both the dependence to carry out daily activities for the patients and their quality of life are detailed below:

MODIFIED RANKIN SCALE (mRS)

The modified Rankin Scale is commonly used to measure the degree of disability or dependence in daily activities in people who have suffered a stroke [24]. It should be accompanied by a structured interview, to avoid subjectivity in scoring, ranging from 0 to 6 indicating more disability for higher scores.

This scale classifies the patient into the following functional grades (see Table 2): Asymptomatic: 0, normal functional capacity; Very mild disability: 1, the patient has some symptoms, but is able to perform usual tasks and activities without limitations; Mild disability: 2, the patient has limitations in previous usual and work activities, but is independent in basic activities of daily living (BADLs) and is able to walk without assistance; Moderate disability: 3, the patient needs assistance for some of the instrumental activities, but not for the BADLs and needs some help for walking; Moderately severe disability: 4, the patient needs assistance with BADLs, and is not able to walk, but does not need continuous care.; Severe disability: 5, the patient needs 24-hour care. The patient is totally dependent, requiring continuous assistance; Dead: 6, the patient has passed away.

MODIFIED RANKIN SCALE (mRS)

mRS Score	Description
0	No symptoms
1	No significant disability. Able to carry out all usuall activities, despite some symptoms
2	Slight disability. Unable to carry out all previous activities but able to look after own affairs without assistance
3	Moderate disability. Requiring some help but able to walk without assistance
4	Moderately severe disability. Unable to walk without assistance and unable to attend to own bodily needs without assistance
5	Severe disability. bebridden, incontinent and requiering constant nursing care and attention
6	Dead

Table 2. mRS [24].

MUSCLE BALANCES

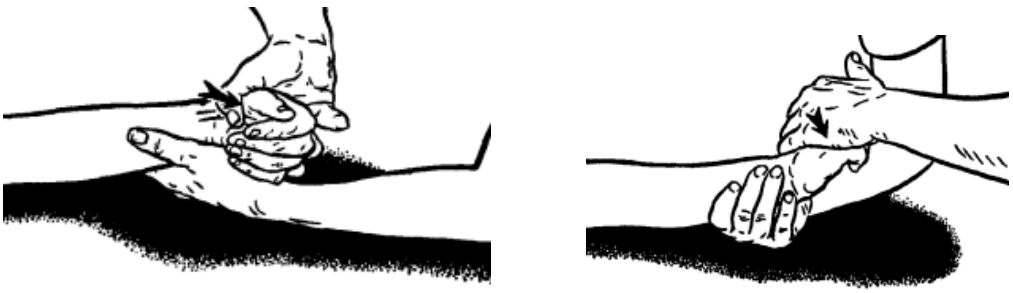
Muscle balance tests are a tool used to measure the strength of muscles in the human body, especially in patients with neuromuscular disorders or localized injuries, but is also used in other conditions that produce motor deficits [31]. The score given to each muscle balance follows the Daniels' scale (see Table 3).

0	Muscle does not contract, complete paralysis.
1	Muscle contracts, but there is no movement. The contraction can be felt or visualised, but there is no movement.
2	The muscle contracts and performs the full movement, but without resistance, as it cannot overcome gravity.
3	The muscle can perform the movement against gravity as the only resistance.
4	The muscle contracts and performs the complete movement, in its full amplitude, against gravity and against moderate manual resistance.
5	The muscle contracts and performs the full range movement against gravity and with maximum manual resistance.

Table 3. Daniels' scale.

This scale has 6 differentiated levels ranging from 0 to 5, with lower scores indicating higher severity of deficit. The tests performed to detect functional deficits of the hand are:

- Flexion and extension of the wrist



a) b)

Figure 11. a) Flexion of the wrist b) Extension of the wrist [31].

- Flexion and extension of the metacarpophalangeal joints of the fingers

a) b)

Figure 12. a) Flexion of the metacarpophalangeal joints of the fingers b) Extension of the metacarpophalangeal joints of the fingers [31].

- Flexion of the proximal interphalangeal joints and distal interphalangeal joints of the fingers

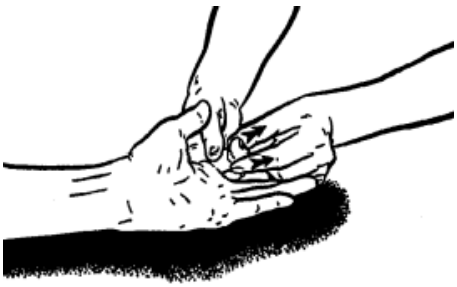


Figure 13. flerxion of the proximal interphalangeal joints and distal interphalangeal joints of the fingers [31].

- Abduction and adduction of the fingers

a) b)

Figure 14. a) Abduction of the fingers b) adduction of the fingers [31].

EUROQOL 5D

The EQ-5D [32] is a generic instrument for measuring health-related quality of life that can be used both in relatively healthy individuals (general population) and in patients with different pathologies [25].

The individual assesses his or her own state of health, first in levels of severity by dimensions (descriptive system) (see Figure 15 a) and then in a more general assessment through a visual analogue scale (see Figure 15 b).

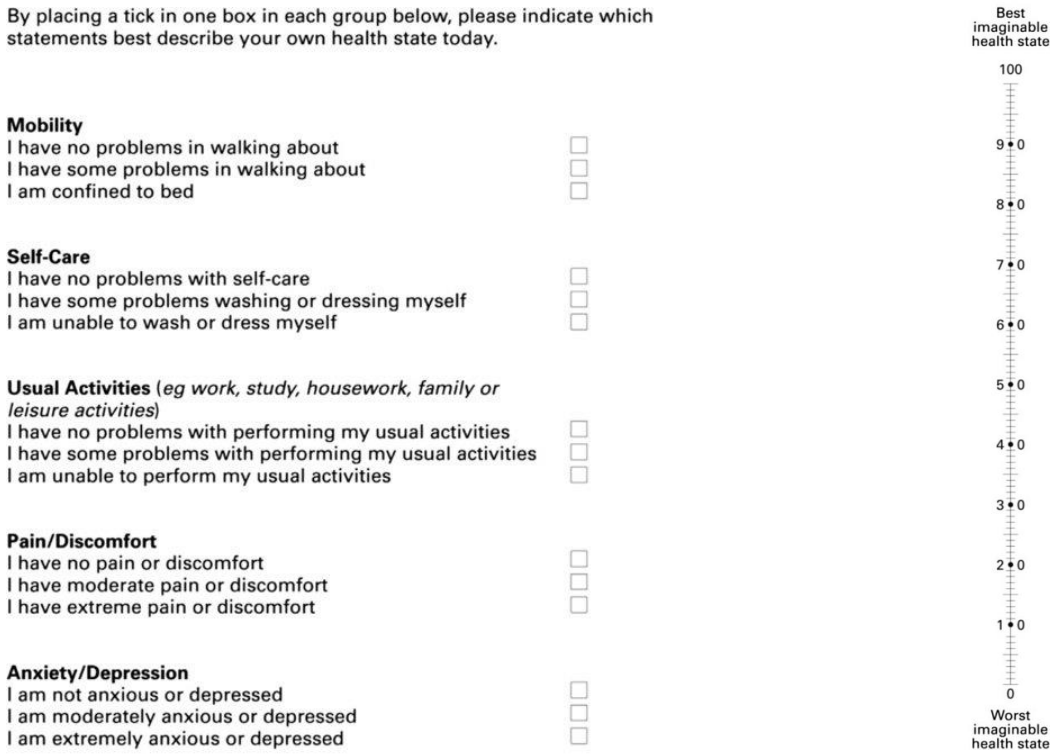


Figure 15 EQ-5D [32].

The descriptive system contains five health dimensions: mobility, self-care, activities of daily living, pain/discomfort and anxiety/depression; and each has three levels of severity: no problems: 1, some or moderate problems: 2 and severe problems: 3. To calculate the score for the descriptive health status some steps have to be followed.

- The combination of the values of all dimensions generates 5-digit numbers, used to calculate the health status value. For this calculation, a value of 1 is assigned to the best condition, being (1,1,1,1,1) status, the best imaginable status with no problems associated.

- If a status is different from 1, the constant value is subtracted (see Table 4).

- Subsequently, if there are level 2 problems in a given dimension, the value corresponding to each dimension (see Table 4) is subtracted.

- If there are level 3 problems, the value of the dimension should be first multiplied by 2 to be then subtracted (see Table 4).

- Finally, the coefficient corresponding to parameter N3 (see Table 4) is subtracted only once when there is at least one dimension with level 3 problems.

For example, in the case of health status 13111 starting from the value 1, the constant and 0.2024 (0.1012 * 2) would be subtracted because there are level 3 problems in the 'Personal care' dimension (See Table 4). In addition, the parameter N3 would be subtracted, which would finally give an index of 0.4355 (0.4355 = 1 - 0.1502 - 0.2024 - 0.2119).

The calculation of the descriptive value is laborious, and it would therefore be useful to automate it, for this purpose a software tool will be developed, which will be explained later.

TABLE OF CONSTANTS (EQ-5D)

Parameter	Value
Constant	0,1502
Mobility	0,0897
Personal Care	0,1012
Usual Activities	0,0551
Pain	0,0596
Anxiety/Depression	0,0512
N3	0,2119

Table 4. Table of Constants (EQ-5D).

The second part of the EQ-5D is a 20-centimetre vertical visual analogue scale (VAS), millimetre-marked, ranging from worst imaginable health status: 0 to best imaginable health status: 100. The patient should mark the point on the vertical line that best reflects their assessment of their overall health status at that time. The use of the

VAS provides a complementary score to the descriptive system of self-assessment of the individual's health status.

The use of these scales is essential to obtain a rapid and objective assessment of the patient who has suffered a stroke, they will also be the basis for comparison with new methods of objective movement assessment that will be developed with emerging technologies. However, it is important to be aware of their limitations as they are ultimately subject to the subjectivity of the clinician or the patient at the time of the examination. Most of them are used to have a quick and general assessment of the patient but are insufficient to detect slight deficits that may affect the patient's activities and capacities.

3 STATE OF THE ART

3.1 Objective Computational Movement Assessment

The purpose of human movement analysis is to quantify the function and structure of the musculoskeletal system during the performance of a specific movement task by capturing and recording the movement. This information will help to identify and quantify alterations or limitations in people's movement patterns and to correct them, particularly, in stroke patients. Describing movement patterns and motor deficits in the upper limb allow to make a prognosis about evolution and help to design individualized therapies more optimized in order to improve outcomes [33].

Objective computational movement assessment may aid clinical evaluation by eliminating the bias of the measurement obtained by the human eye and improving the discriminative capacity of clinical scales particularly with regard to minor deficits.

There are numerous studies that aim to delve into the objective computation of movement [34] [35] [36], as well as devices capable of measuring parameters associated with the movement of the hand (see Section 3.1.1). Furthermore, rehabilitation techniques are evolving, and new technologies based on virtual reality are being incorporated.

Therefore, a review of the state of the art has been performed to find out how objective movement assessment and virtual reality environments are incorporated in neurological rehabilitation processes.

3.1.1 MOTION CAPTURE SENSORS

Available motion capture devices can be classified into two main groups according to the type of sensor they use: optical and inertial sensors [37].

OPTICAL SENSORS

Within this group, depending on the optical motion capture technology that each sensor uses, a distinction can be made between Visual/Depth Cameras and Optical Motion Tracking Systems [37].

Visual/Depth Cameras

These devices do not require any additional elements and they capture the motion directly from a point cloud (set of data points defined in a coordinate system). Using M to refer to the number of points and N for the number of dimensions of the space, the point cloud can be expressed as [38]:

$$P = \{p_1, \ldots, p_M\} \quad p^T \in \mathrm{R}^N \tag{3.1}$$

Two conditions are required to form an N-dimensional point cloud and that the points could be stored in memory through an array (P) where each row vector corresponds to a point:

1- $$p_i^T \in \mathrm{R}^N \quad i = 1, \ldots, M \tag{3.2}$$

2- The object of interest must be in the convex hull of the points, this means that the object to be tracked (in this case both hands) must be in a delimited zone.

The Kinect (v1,v2) device is the most relevant within this group. Originally launched as a gaming device, has become one of the most widely used devices in studies that measure the movement of the human body in several biomedical applications [36] [39] [40] [41]. The device has been validated in numerous gait-related applications and for measuring motor deficits associated with neurological diseases [42]. However, all these applications have been validated for large movements involving whole limbs or even the entire human body in gait phase but not for precise movements related to the hand, since one of the main problems of the tool is that it does not have the ability to discriminate small segments of the body [43].

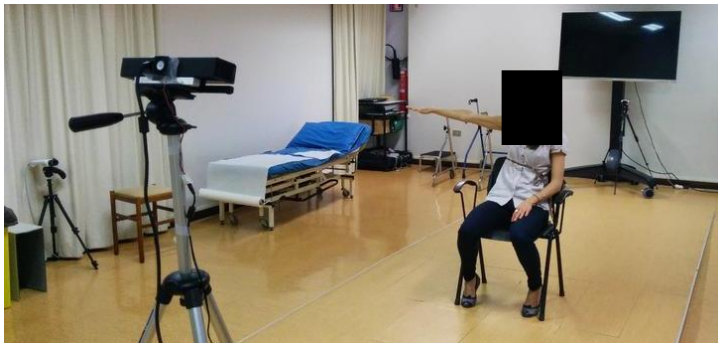


Figure 16 Set up for assessing upper limb movement with Kinect v2 [41].

Marked Based motion capture systems

Several marked based motion capture systems such as OptiTrack [44], Optotrack [45], PhaseSpace [46] are available, but the most common and used as a gold standard is the Vicon [47] system.

This kind of systems works with a set of markers attached to predefined locations on the human body, while several cameras are in charge of tracking the markers' positions during the whole movement process. These cameras are positioned at different viewed angles, and they typically employ infrared technology to obtain the position of the markers. A software uses trigonometrical relations among the markers and the cameras to obtain the position and orientation of each body joint [37].

These cameras provide a collection of 2D coordinates. However, it is necessary to transform them into 3D {X, Y, Z} coordinates in a world reference frame, where the movement is taking place [48]. Photogrammetry is a technique in the field of machine vision that provides the required tools to relate 2D and 3D coordinates:

Being P = {X, Y, Z} a Cartesian point in R^3 in an inertial reference frame, knowing the position P_0 and orientation R_{3x3} of a camera in that reference, it is possible to evaluate the orthogonal projection P' = {X', Y', Z'} in the camera plane as shown in Eq. 3.3.

$$P' = R\,(P - P_0) \tag{3.3}$$

The value for the Z' component is therefore, the distance from the camera to the point, and adding the effective focal length allows to compute the projective coordinates { $\bar{x}$' , $\bar{y}$'} as:

$$\begin{Bmatrix} \bar{x}' \\ \bar{y}' \end{Bmatrix} = \frac{f}{\bar{Z}'} \begin{Bmatrix} X' \\ Y' \end{Bmatrix} \tag{3.4}$$

However, optic distortion introduced by the camera lenses has to be taken into account. Instead of getting { $\bar{x}$' , $\bar{y}$'} directly from the sensors, they are actually providing is a distorted version { $\bar{x}$, $\bar{y}$} of them. This optic distortion is divided into radial (see Eq. 3.5) and tangential (see Eq. 3.6).

$$\begin{Bmatrix} \bar{x}'^r \\ \bar{y}'^r \end{Bmatrix} = \begin{Bmatrix} \bar{x}' \left(k_1 r^2 + k_2 r^4 + \ldots\right) \\ \bar{y}' \left(k_1 r^2 + k_2 r^4 + \ldots\right) \end{Bmatrix} \tag{3.5}$$

$$\begin{Bmatrix} \bar{x}'^t \\ \bar{y}'^t \end{Bmatrix} = \begin{Bmatrix} 2p_1 \bar{x}' \bar{y}' + p_2 \left(r^2 + 2\bar{x}'^2\right) \\ p_1 \left(r^2 + 2\bar{y}'^2\right) + 2p_2 \bar{x}' \bar{y}' \end{Bmatrix} \tag{3.6}$$

Taking all this into account, the final expression capable of relating 2D coordinates can be constructed as shown in Eq. 3.7.

$$\begin{Bmatrix} \bar{x} \\ \bar{y} \end{Bmatrix} = \begin{Bmatrix} f_x \left(\bar{x}' + \bar{x}'^r + \bar{x}'^t\right) \\ f_y \left(\bar{y}' + \bar{y}'^r + \bar{y}'^t\right) \end{Bmatrix} + \begin{Bmatrix} \bar{x}_0 \\ \bar{y}_0 \end{Bmatrix} \Longrightarrow$$
$$\Longrightarrow \begin{Bmatrix} \bar{x} \\ \bar{y} \end{Bmatrix} = D\left(\begin{Bmatrix} \bar{x}' \\ \bar{y}' \end{Bmatrix}\right) \tag{3.7}$$

These expressions connect the 3D coordinates of a point P with its analogue 2D version on each camera, knowing its spatial location.

Marked Based motion capture systems have been used in several validation studies related with body positioning both in static and dynamic tests [49] [35], being considered as a gold standard for verifying the reliability of other motion analysis systems. However, such systems are invasive for the patient (Figure 17), require a specialist to place the markers in the suitable spots, require a large amount of space to place the cameras at the correct angles and involve high costs.

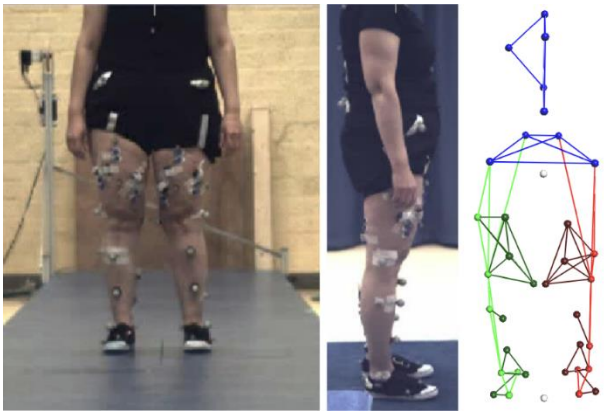


Figure 17 Experimental setup for gait measurements [49]

INERTIAL SENSORS

An inertial sensor or also known as an IMU (inertial measurement unit) is a component capable of obtaining the position, orientation and velocity of any device where it is used. [50]

Inertial sensors (see Figure 19) typically consist of a gyroscope, an accelerometer and most of them contain a magnetometer. The mathematical models to explain how inertial sensors work are more complex than the optical motion capture sensors. They can be summarized in the continuous-time inertial navigation equations (see Eq. 3.8, 3.9, 3.10); these equations describe a moving body's time evolution relative to a frame at rest [51].

$$\dot{R}^{nb} = R^{nb}[\omega^b \times], \tag{3.8}$$

$$\dot{p}^n = v^n, \tag{3.9}$$

$$\dot{v}^n = g^n + R^{nb}s^b. \tag{3.10}$$

- Gyroscope: they are sensors that quantify the angular variation of an object over a period of time, they help to quantify angular velocity by being sensitive to rotational motion and changes in orientation of an object. Therefore, the angular position can be determined by using the mathematical operation of integration. Gyroscopes work by means of the Coriolis effect, which can be explained as: given a rotating inertial reference frame and an object moving relative to that frame, the object will suffer from an inertial force that is orthogonal to the axis of rotation of the frame and the velocity of the object, causing the object to have a deflection in its trajectory (see Figure 18) [52].

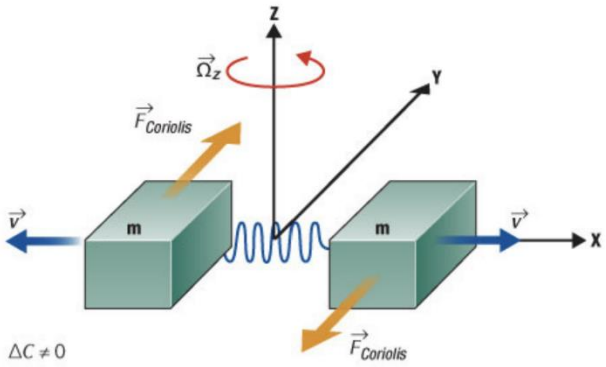


Figure 18 Coriolis effect on a Gyroscope [52]

- Accelerometer: they are sensors used to measure the change in velocity of bodies over a certain period of time, as well as to determine the forces applied to an object with a certain mass in order to move it [52].

- Magnetometer: they obtain information about the magnetic north, so that it is always positioned with respect to the earth's magnetic field.

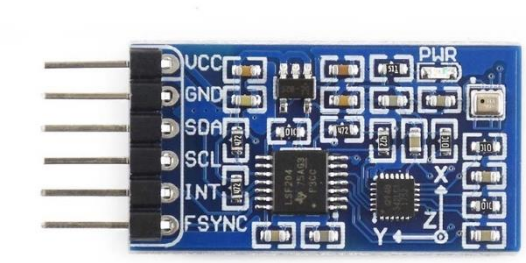


Figure 19 Example of an inertial sensor [70].

In summary, there are numerous ways of capturing motion using different technologies. In general, these methods have several limitations as most of them are either too cumbersome, not useful enough to capture precise movements or too expensive to be introduced into the everyday patient environment. It will therefore be necessary to see how each one behaves in different environments in order to make the most appropriate selection of the tool.

3.1.2 RELEVANT UPPER LIMB COMPUTATIONAL MOVEMENT ASSESSMENT STUDIES

Several studies that offer relevant insights for setting the standards for computational motion analysis have been carried out. Some of them were cited in the previous section, but it is useful to highlight and dwell on a few of them pointing out those aspects that have been considered of interest for the development of this thesis.

Each of these studies will provide different insights: the way in which statistical analyses are carried out, the most important clinical and kinematic variables to collect and other ways to measure movement with the previously mentioned capture methods to draw more rigorous conclusions. In addition, studies in which the rehabilitation process is relevant will be reviewed, as the tool developed will not only objectify movement but will simultaneously serve as an individualized rehabilitation device.

- ***Hand focused upper extremity rehabilitation in the subacute phase post-stroke using interactive virtual environments*** [53]**.** This study is designed to test the value of high-dose intensive training and the

optimal timing of intensive VR/Robotics training in the first 2 months after stroke. This is an ongoing project that uses several methods and devices to measure kinematics, secondary outcomes (see Figure 20) including : an ATI nano17 force sensor, the CyberGlove [54] and an array of motion sensors, the Optitrack and a robotic arm to reach 5 haptically rendered spheres.

The combination of these technologies makes the results of the study very precise and reliable, but it is not feasible to incorporate them into daily clinical practice, as they are too cumbersome and expensive, and would require specialized personnel and extra time for the evaluation of each patient.

Measure	Domain measured	Pre-test**	Post-test	1 month	4 months
Primary outcome					
Action research arm test	Upper limb function	x	x	x	x
Secondary outcomes - clinical					
Box and blocks	Gross manual dexterity	x	x	x	x
Upper extremity fugl-meyer assessment	Upper limb impairment	x	x	x	x
Patient's structured assessment	Perception of limb function		x		
EuroQol	Health-related quality of life	x	x	x	x
NIH health stroke scale	Neurological status	x			
Secondary outcomes – kinematic/kinetic					
Maximum isometric pinch force	Maximum force produced	x	x	x	x
Pinch force regulation	Modulation of force production	x	x	x	x
Range of motion (ROM)	Active/Passive ROM upper limb	x	x	x	x
Real-world reach-to-grasp test	Kinematics of grasping	x	x	x	x
Robot based daily kinematic measures	Immediate effects of training	x	x		
Home-based accelerometry	Amount of daily arm use		x*		x

Figure 20 Assessment schedule for the outcome measures [53].

- ***Validity and Reliability of Kinect v2 for Quantifying Upper Body Kinematics during Seated Reaching*** [34]**.** This study, published in 2022, aims to assess the validity and reliability of the Kinect v2 for the analysis of upper limb reaching kinematics. For this purpose, exercises

were recorded simultaneously with the Kinect v2 and the Vicon. They assessed the validity and reliability of the Kinect v2 for key variables in upper limb kinematic assessment after stroke with the hypothesis that the Kinect v2 will provide the same information as the Vicon system. A summarized version of the results are shown in Figure 21.

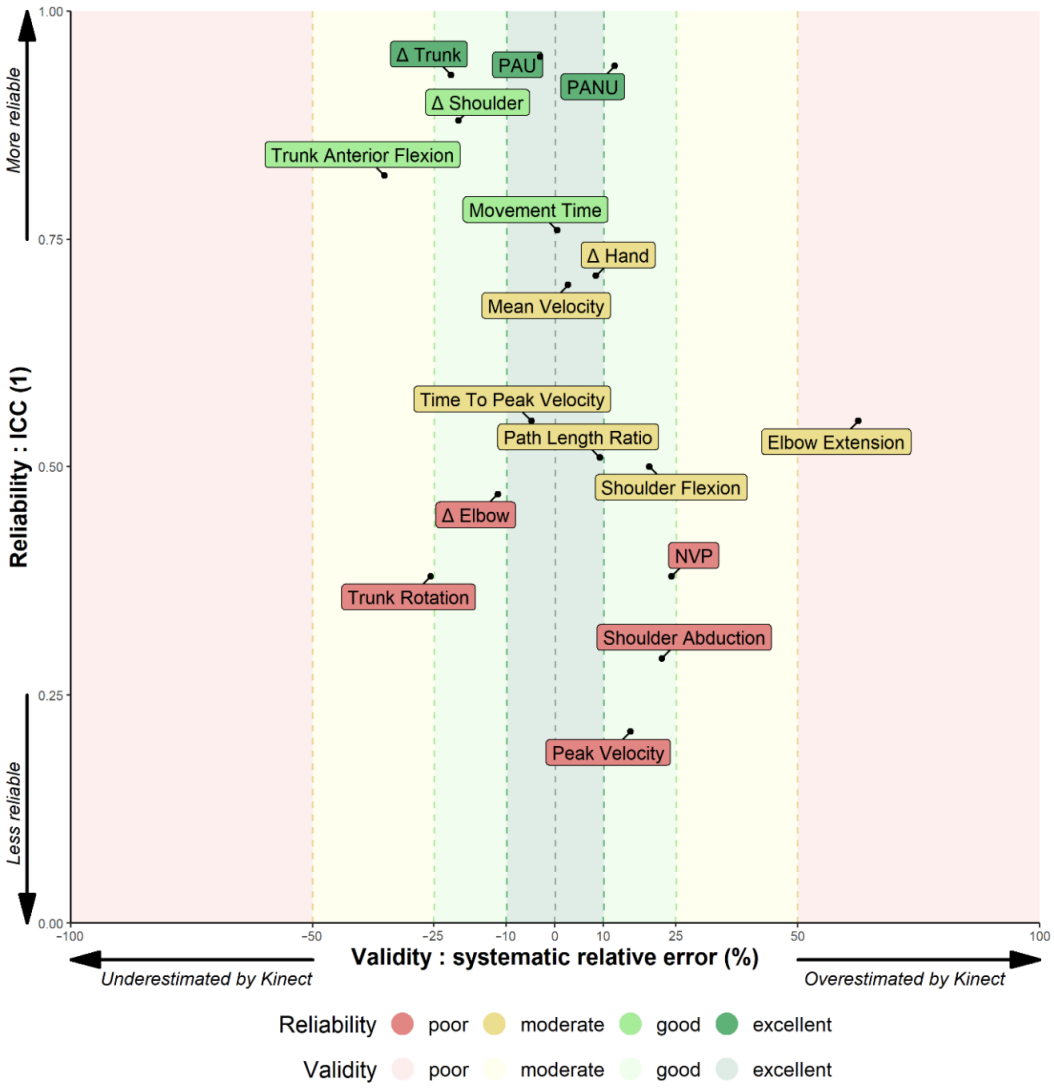


Figure 21 Summary of the validity and reliability of 17 kinematic variables assessed by the Kinect [34].

As it can be observed, the measurements of the finer movements or those which require greater precision are the least reliable with the Kinect v2. Hand movement assessment is affected by this limitation. Therefore, although tools such as the Kinect are manageable and of relative low-cost to be introduced in a clinical environment or for daily practice or even to be used by patients, they are not accurate enough to assess mild hand impairments.

- ***Assessment of Upper Limb Movement Impairments after Stroke Using Wearable Inertial Sensing*** [55]**.** This pilot study was set up to investigate upper limb movements from proximal to distal functions in stroke subjects by using a wearable inertial sensing system. Patients with at least partial ability to move the arm against gravity and able to perform finger movements for basic gripper functions are included. For this evaluation, the FMA-UE scale is used, complemented by the Modified Ashworth Scale, which is a clinical scale that measures spasticity, a factor to be considered in the evolution of a stroke patient in the long term.

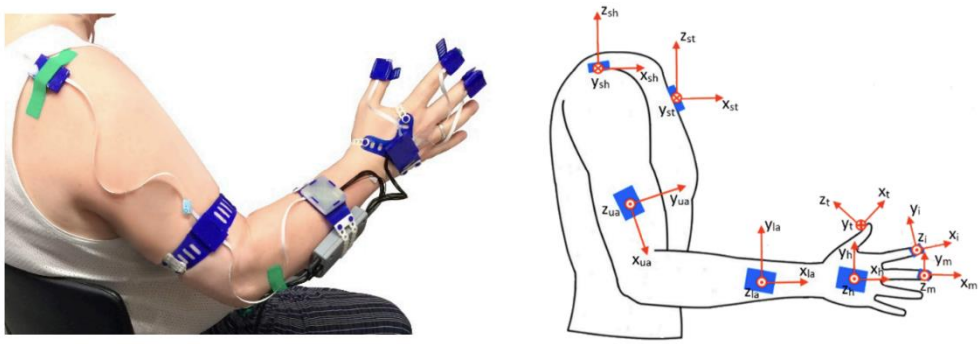


Figure 22 Wearable inertial sensing system [55].

The motion capture method used was composed of eight IMUs, with triaxial accelerometers and gyroscopes, resulting in a quite invasive measurement system (see Figure 22). Additionally, these sensors required to be calibrated every day, and the kinematic reconstruction

was based on the estimation of the sensors' orientation, which may introduce errors if this procedure is not carried out adequately.

In addition, the authors discuss the motion analysis of the theoretically unaffected limb, performing statistical analysis between the affected and non-affected side, an issue that has also been considered in the development of this thesis.

The review of these studies provides an insight into the advantages and disadvantages of different types of motion capture methods and their limitations when introduced in a clinical examination environment. It also helps in the choice of the tool used in this thesis, as in the end there is a need for a relatively inexpensive, easy to use, minimally invasive tool that is able to reliably measure accurate hand movements of patients.

3.2 Computational Assessment Software Using a Leap Motion device

Technological development has facilitated the analysis of movement through the creation of tools that allow its detection and parameterization. However, as has been explained in the previous section, most of the systems used today rely on information obtained through sensors placed on the limb or devices that combine robotics and exoskeletons. These systems are expensive, complex and require trained personnel to use them, so they do not meet the objectives of simplicity and accessibility necessary for their use in routine clinical practice. Therefore, a portable device (Leap Motion, see Section 3.2.1) for capturing kinematic data is proposed for its validation in a clinical environment, to determine whether the tool is able to detect and quantify mild hand movement deficits in stroke patients. This device uses optical technology to capture movement, so no extra equipment is required except for the computer to plug it into.

3.2.1 Leap Motion

The Leap Motion Controller [56] is an optical hand tracking module that captures the movements of the hands with unparalleled accuracy. The controller is capable of tracking hands within a 3D interactive zone that extends up to 60cm (24”) or more, extending from the device in a 140x120° typical field of view [57].

It is a device that connects directly to a computer via USB 2.0, based on two 640x240-pixel near-infrared cameras, separated 40 millimeters apart and three LEDs spaced on either side and between the cameras to prevent overlaps. These cameras operate in the 850 +/- 25 nanometer spectral range and at a sample frequency of 120 Hz.

This type of optical motion capture does not require the use of markers or any other type of sensor that could be invasive for the patient, and its small dimensions (80 x 30 mm) and light weight (32 grams) make the device an optimal tool to be used in any situation

Figure 23 Leap Motion device [56]

Unlike the Kinect device, the Leap Motion is capable of tracking particularly small objects, with higher accuracy [58]. The Kinect is focused on capturing large objects, so it is less sensitive to small movements, such as moving fingers or a pen, which was the main recurring problem in all studies that tried to capture fine movements to measure deficits.

Coordinate System

The Leap Motion system employs a right-handed Cartesian coordinate system, the origin is centered at the top of the device. The X and Z axes are located in the horizontal plane, being the X-axis parallel to the long side of the device. The Y-axis is vertical, with positive values increasing upwards. The Z-axis has positive values increasing toward the user [57] (Figure 24).

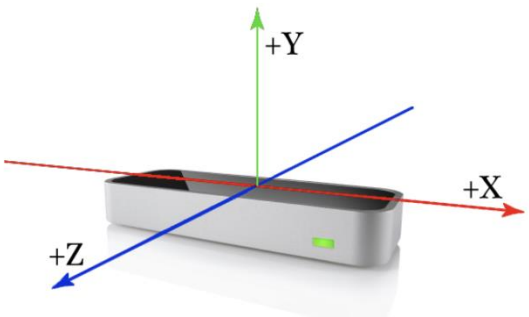


Figure 24 Leap Motion Coordinate System [57]

Motion Tracking Data

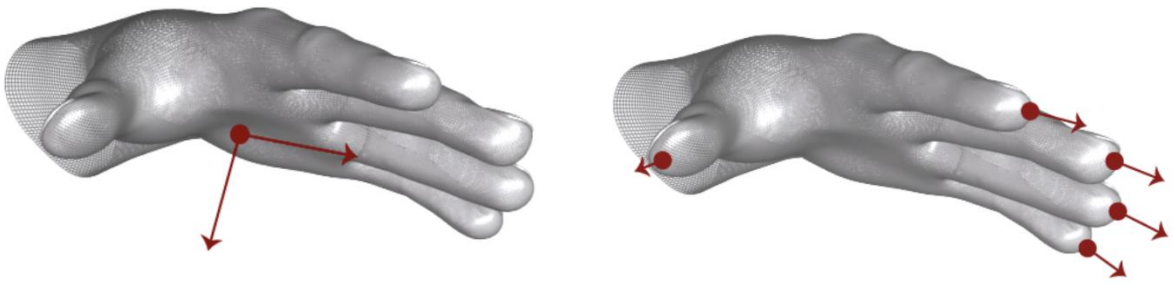
The Leap Motion controller tracks hands and fingers in its field of view providing updates as a frame of data. This 'Frame object' details all of the properties at a single moment of time, being the root of the Leap Motion data model.

The hand model, which is represented by de 'Hand class', provides information about the identity and position. The orientation of the hand is defined by two vectors: *PalmNormal* and *Direction* (see Figure 25). In addition, the Leap Motion software uses an internal model of a human hand to provide predictive tracking even when parts of a hand are not visible. However, the tracking is optimal when the hand and every single finger are clearly visible for the device. The controller also provides information about each finger on a hand. If a part of a finger is not visible, the finger characteristics are estimated based on recent observations and the anatomical model of the hand. Fingers are identified by type name, i.e. *thumb*, *index*, *middle*, *ring*, and *pinky* and are represented by the 'Finger Class'. The position of a finger tip and the general direction in which a finger is pointing are provided by *TipPosition* and *Direction* vectors.

A Finger object provides a 'Bone object' describing the position and orientation of each anatomical finger bone. Identifying the following bones:

- *Metacarpal*. The bone inside the hand connecting the finger to the wrist (except the thumb)
- *Proximal Phalanx*. The bone at the base of the finger, connected to the palm
- *Intermediate Phalanx*. The middle bone of the finger, between the tip and the base
- *Distal Phalanx*. The terminal bone at the end of the finger

For ease of programming, the Leap Motion thumb model includes a zero-length metacarpal bone so that the thumb has the same number of bones at the same indexes as the other fingers.



a) b)

Figure 25: a) Orientation of the hand defined by PalmNormal and Direction vectors, b) Position of a finger tip and the general direction in which a finger is pointing defined by FingerTip and Direction vectors [57]

These features make Leap motion an ideal device for optical motion capture in the clinical environment. Therefore, it will be the motion capture method used for the development of this master thesis.

4 METHODOLOGY

All of the methods employed in the validation of the tool are described in this chapter; the previous development of the tool and the implementation of improvements, the design of the validation studies carried out, the conformation of the database, and the selection of the different parameters to be studied as well as their processing, are detailed here.

4.1 PREVIOUS DEVELOPMENT OF THE SOFTWARE TO ASSESS HAND MOVEMENT

As part of a collaborative project between the Neurology Service of the 'Hospital Universitario La Paz', 'IdiPAZ' and the Control and Robotics Lab (ROBOLABO) of the 'Universidad Politécnica de Madrid' a preliminary software to assess hand movement has been developed.

So far, the battery of exercises to be evaluated has been selected and the visual interface for performing them on a virtual reality platform has been designed. In addition, a preliminary version of the software has been previously designed to obtain kinematic variables in real time of the different segments of the hand during the performance of the exercises [59]. This software will be the main material for the collection of kinematic data of the hand in both patients and healthy subjects, the version used is detailed below in order to subsequently understand the improvements made.

4.1.1 Support for arm support

A complementary support structure for the arms of the subject was designed for two main reasons:

- To constantly maintain the hands in an optimal position for the Leap Motion's field of vision.
- To help the patient to maintain a fixed posture in both arms, preventing them from falling, and to isolate the movement of the hand.

This provides homogeneity of the measurements obtained that facilitates data processing, and eliminates low-frequency noise due to involuntary arm movements.

Figure 26. Support structure for the arms [59]

4.1.2 Exercise Selection

A total of four exercises are included and implemented in the system for further analysis, which are typical basic exercises in hand movement assessment. The choice was based on the advice of neurologists, the items used in the main clinical scales for assessing neurological damage and the ability of Leap Motion to capture movement. For this last restriction, the exercises must remain within the field of vision and the fingers must be visible at any moment so that the capture process could be more accurate. The movement of each exercise must be performed repeatedly for the entire duration of the exercise.

The exercises selected are as follows:

- Exercise 1. Wrist Flexo – Extension: The subject starts with the hands in a horizontal position and the fingers stretched out without excessive tension, so that the device can better capture the movement. A wrist extension movement is carried out, raising the palm of the hand as much as possible and returning to the starting position. (see Figure 27).

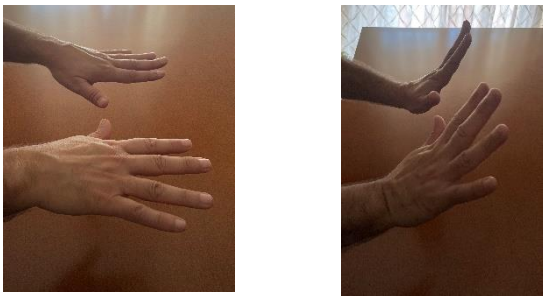


Figure 27 Exercise 1. Hand flexo - extension

- Exercise 2. Finger Grip: The subject starts with hands extended and fingers spread apart, the wrist may be slightly bent to facilitate the capture of the hands by the Leap Motion. A grip movement between the thumb and index is carried out, the rest of the fingers should remain still as much as possible. (see Figure 28).

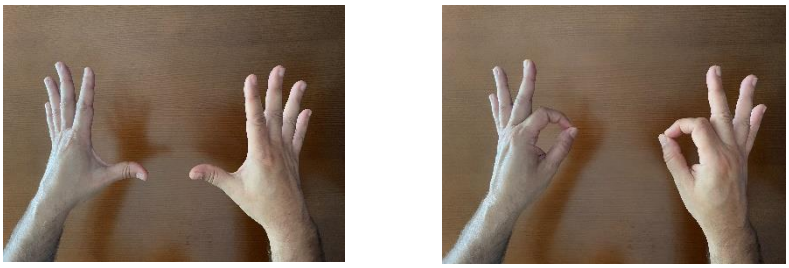


Figure 28 Exercise 2. Finger grip

- Exercise 3. Finger Separation: The subject starts with the hands extended and the fingers together and stretched out without excessive tension. With the arm held still, a movement of finger spread will be carried out, separating each of the fingers from the others as much as possible and returning to the starting position. (see Figure 29).

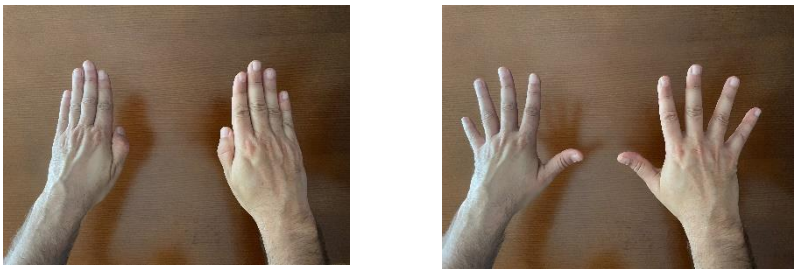


Figure 29 Exercise 3. Finger Separation

- Exercise 4. Fist Opening and Closure: the subject starts with the hands extended in an horizontal position with the fingers separated and stretched out. A movement of fist closure is carried out, returning to the starting position. The movement must be performed repeatedly for the entire duration of the exercise (see Figure 30).

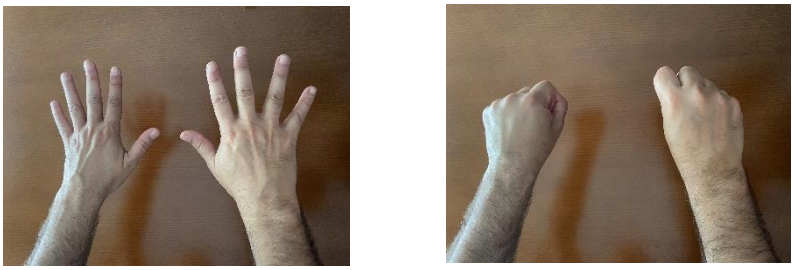


Figure 30 Exercise 4 Fist Opening and Closure

4.1.3 Data collection and storage

The variables to be further processed are collected with a sampling frequency of 50 Hz, and will be the same for all of the exercises:

- Finger tip position
- Middle point of the palm position
- Velocity vector of the palm
- Normal vector of the palm

Each of these variables are split into its x, y and z components and are stored in a .csv file, one for each exercise performed, with the following name format: AAAAMMDD-hhmmss-ID-EX.csv, where 'AAAAMMDD' corresponds to the date when the exercise is performed, 'hhmmss' corresponds to the exact time of the exercise completion, 'ID' corresponds to the single identifier previously added at the beginning of the test and 'EX' refers to the number of exercise associated with that file. All of these csv files are stored in a relative route \Leap Motion Data Tracker Data\StreamingAssets\LeapData. It is relevant to acknowledge how the data is stored to understand the problems associated with this, and to carry out the necessary improvements for better data management.

4.1.4 Software interface and functionality

This tool and its implementation in Unity is detailed in previous works [59]. However, it is important to explain how it worked to explain and analyze its functioning to understand its limitations and justify the improvements that have been incorporated in this MSc thesis.

The first version of the environment (v 1.0) used for motion capture contains a series of interactive screens explained below:

- **Main Menu**: The first screen that appears when opening the software corresponds to the main menu. It has three functionalities associated with three different buttons, configuration of the application ('Configuración'), beginning of the test ('Comenzar') and exit the application ('Salir'), respectively.

  When clicking 'Salir', the application closes immediately, ending all process. If the user clicks on 'Comenzar' without configuring the app, the test starts with the default settings, which corresponds to a five second duration for each exercise, normal mode of execution that will be explained in the following screen and without an identifier for the user. The 'Configuración' button leads to the settings screen of the software in order to set the required parameters to start the test.

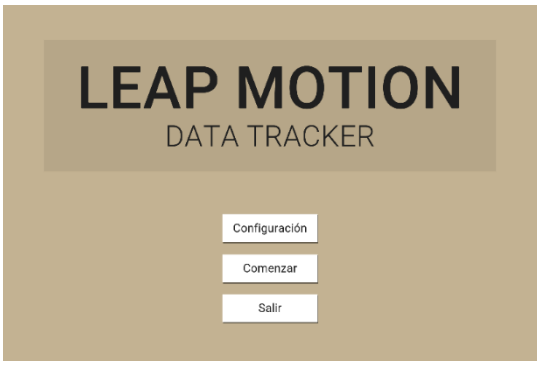


Figure 31 Main Menu (v 1.0).

- **Settings Screen**: This screen includes a set of fields to be filled in (see Figure 32 a). The first one refers to the execution time for each exercise in seconds, if the users introduces an invalid value, the app returns an error message. The second field corresponds to the identifier of the subject that will appear at the end of the .csv file. In addition, two execution modes will be available: normal and solo.

  Normal mode: this mode is intended to perform the test under the supervision of the clinician, who will be the one to verify if the exercises are correctly performed and will be in charge of progressing between screens until the end of the execution.

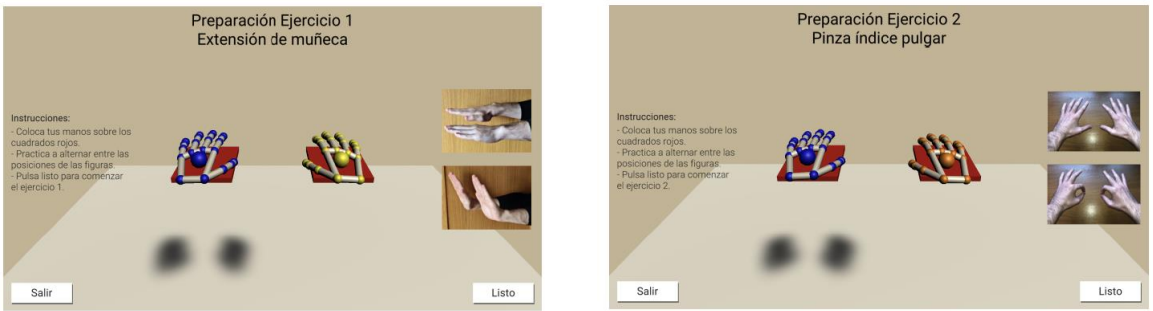
  Solo mode: this mode does not require the presence of a second person. It is totally automated so the patient can perform the exercises without moving the hands out of the leap motion's field of vision. In addition, the verification screen does not appear in this mode.

a) b)

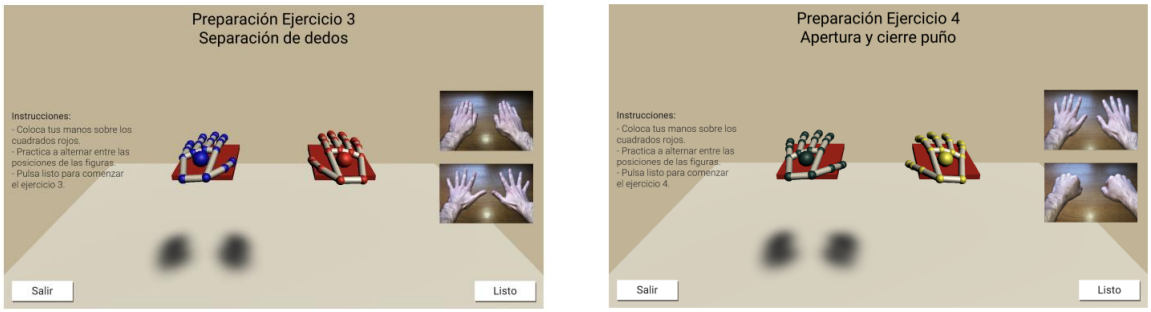
Figure 32 Configuration Screen a) Fields to be filled in b) Summary of the

Once the settings are configured the user must click on 'Guardar' obtaining a summary of the selected parameters (see Figure 32 b), the button 'Volver' returns the user to the main menu, and the application will be ready for the patient to start the test.

- **Preparation Screen:** In this screen the user should prepare and start performing the corresponding exercise, these data will not be recorded, but the clinician will be able to see whether the patient is performing the exercise correctly. When clicking 'Listo' (see Figure 33) the recording starts for the time previously selected. A brief description of the tasks is also added in this screen.



a) b)



c) d)

Figure 33 Preparation Screen a) Ex 1 b) Ex 2 c) Ex 3 d) Ex4 (v 1.0).

- **Execution Screen** (see Figure 34): The motion capture recording will take place on this screen, the user must perform the exercise during the selected time and Data corresponding to each exercise will be stored in the .csv. This screen is very similar to the preparation screen, however the instructions are removed and a countdown timer appears indicating the period in which data is being collected for each exercise.

a) b)

c) d)

Figure 34 Execution Screen a) Ex 1 b) Ex 2 c) Ex 3 d) Ex4 (v 1.0).

- **Confirmation Screen:** Once the exercise is completed, a confirmation will pop up, and the clinician that supervises the test must confirm whether the exercise is correctly recorded (see Figure 35). The option 'Sí' leads to the next exercise or to the final screen, and clicking 'No' forces the user to repeat the exercise again, this process could be cyclic until the exercise is correctly recorded.

  It is relevant to acknowledge that this confirmation depends entirely on the clinician/user criteria allowing to repeat or not the exercise as needed, but can also pose difficulties when used by patients for self-assessment.

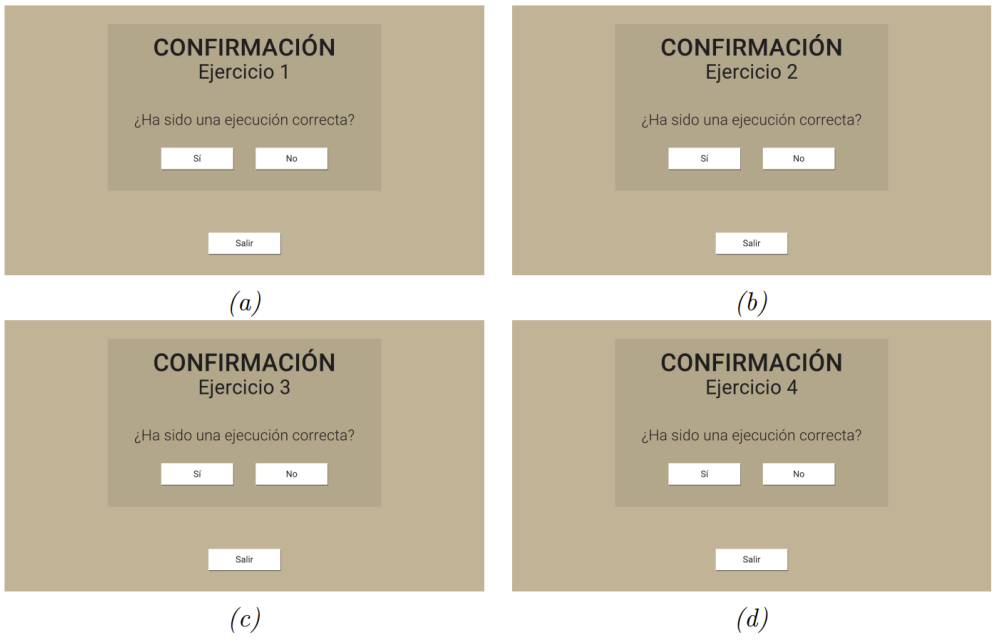


Figure 35 Confirmation Screen a) Ex 1 b) Ex 2 c) Ex 3 d) Ex4 (v 1.0).

- **Final Screen:** Once the fourth exercise is performed and confirmed, a final screen will appear (see Figure 36) that will inform that the study is completed, and offering two options: 'Menú principal' to return to main menu and 'Exit' to shut down the application.

Figure 36 Final Screen (v 1.0).

4.2 Software to Assess Hand Movement. Implementation of improvements.

Within the previously mentioned collaborative project, several improvements are proposed and implemented in the application (v 1.1), for a better user experience. These changes attempt to solve the problems mentioned in the previous section as well as to incorporate new useful functionalities for the evaluation of the hand's deficit.

- New Interface Design

  A new interface for the application is proposed with a more elaborate and professional look introducing the logos of the partner organizations and new functionalities in the main menu. In addition, the logo and brand name are included in this screen.

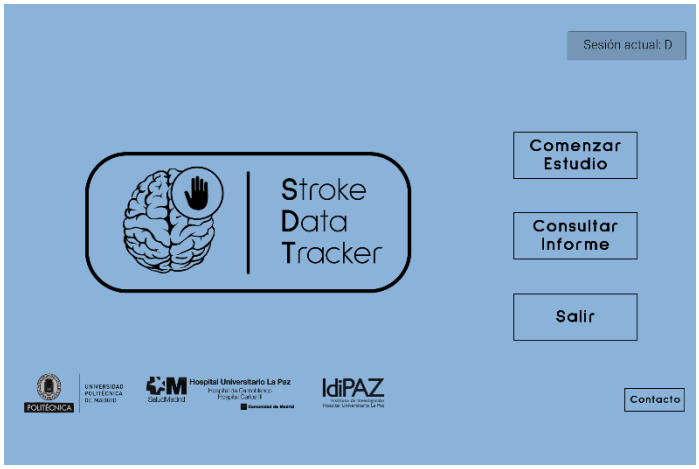


Figure 37. Main Menu of the final application (v 1.1).

- Data Storage

The previous version's approach to storage the data was inefficient for data processing. The name was too long without providing relevant information, and all the csv files were saved in the same folder, which resulted in a lack of organization in the files. In order to solve this problem, a file organization structure (see Figure 38) and a different sort of nomenclature is proposed in order to access the files more efficiently.

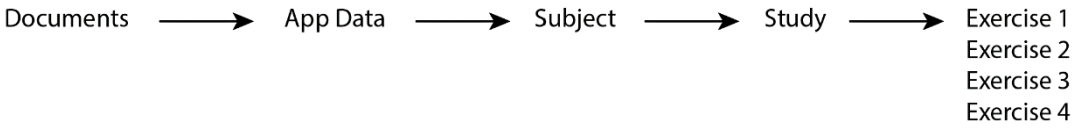


Figure 38. Data storage schema

The .csv file is named following a new criteria: SesionID+Identifier–Nstudy–Date(YYYYMMDD)–NExercise.csv, eliminating the exact time of the test in the name in order to make the file more accessible.

See Figure 39 as an example for the file of a patient identified as P1 for the exercise 4 (Fist Opening and Closure) performed the 20th of June of 2022 in a session identified with a D.

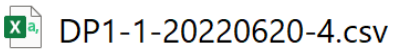


Figure 39. CSV naming example.

- Generation of the Report of Results

A new functionality is introduced in the application, which provides real-time feedback both to the neurologist in charge of assessing the patient's degree of deficit and to the user himself, who will be aware of his situation at the time of performing the test. The results report is automatically generated once the exercises have been completed and is saved in pdf format in the corresponding folder. This document will contain a cover page with the patient's identifier and the date of the study (see Figure 40 a) as well as a detailed analysis (graphical and numerical) of the most relevant parameters for each exercise (see Figure 40 b).

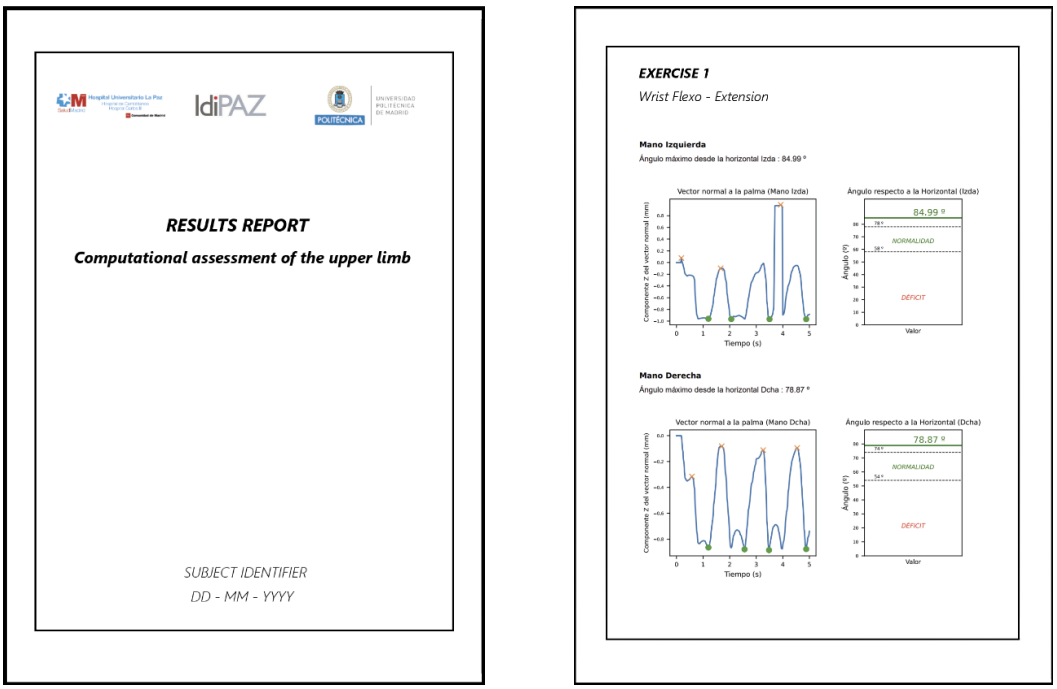


Figure 40. Results report a) Cover b) Example of a result representation.

In addition, the possibility to insert a summary sheet after the cover page, which allows a quick overview of the exercises in which there are deficits is enabled. Also a sheet showing the evolutionary changes for those patients who have carried out two or more studies is available.

- Visualization of the Report

The new interface integrates the visualization of the reports once they have been generated and stored in the corresponding folder. In the main menu a button is added that leads to the reports consultation screen (See Figure 41 a). This screen (See Figure 41 b) contains two extensible lists in which it is necessary to select the subject and the desired study from which the report is being generated and a button that will display the final report.

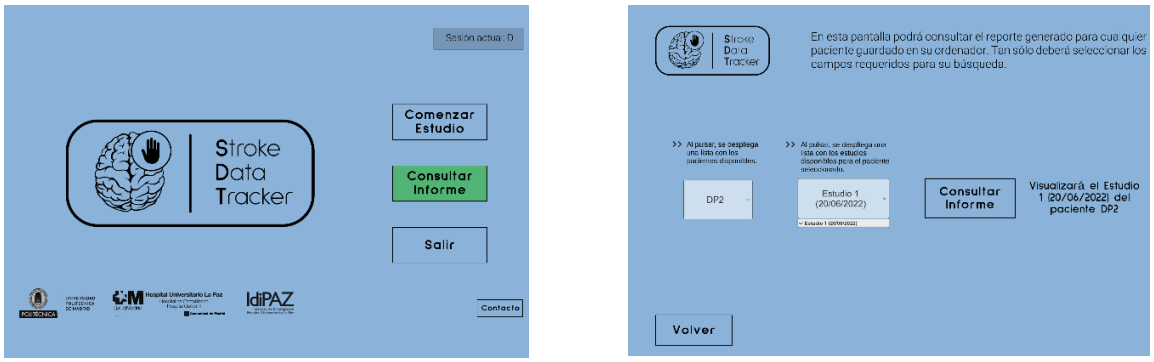


Figure 41. Report consultation a) Main menu 'Report Consultation' button b) Report Consultation screen (v 1.1)

The introduction of all these improvements facilitates the user experience for both the clinician and the patient performing the test, provides real-time feedback on the patient's situation and ultimately streamlines the processing of the data explained in the section below.

4.3 DATA PROCESSING

The .csv files obtained from each exercise are processed to obtain the final parameters which will be further analysed. These raw data consist of twenty-four variables, for each hand plus the variable of 'Time' common to both (see Table 5).

Fifteen inputs correspond to the position of the tip of the finger divided into its three components (x, y, z). The rest of the variables are related to the centre point of the palm including: position, velocity and the normal vector, all of them also divided into x y and z components.

RAW VARIABLES FROM LEAP MOTION

	Left Hand	**Right Hand**
	Time	*Time*
Finger Position	*leftThumbTipPosition_X*	*rightThumbTipPosition_X*
	leftThumbTipPosition_Y	*rightThumbTipPosition_Y*
	leftThumbTipPosition_Z	*rightThumbTipPosition_Z*
	leftIndexTipPosition_X	*rightIndexTipPosition_X*
	leftIndexTipPosition_Y	*rightIndexTipPosition_Y*
	leftIndexTipPosition_Z	*rightIndexTipPosition_Z*
	leftMiddleTipPosition_X	*rightMiddleTipPosition_X*
	leftMiddleTipPosition_Y	*rightMiddleTipPosition_Y*
	leftMiddleTipPosition_Z	*rightMiddleTipPosition_Z*
	leftRingTipPosition_X	*rightRingTipPosition_X*
	leftRingTipPosition_Y	*rightRingTipPosition_Y*
	leftRingTipPosition_Z	*rightRingTipPosition_Z*
	leftPinkyTipPosition_X	*rightPinkyTipPosition_X*
	leftPinkyTipPosition_Y	*rightPinkyTipPosition_Y*
	leftPinkyTipPosition_Z	*rightPinkyTipPosition_Z*
Palm Position	*leftPalmPosition_X*	*rightPalmPosition_X*
	leftPalmPosition_Y	*rightPalmPosition_Y*
	leftPalmPosition_Z	*rightPalmPosition_Z*
Palm Velocity	*leftPalmVelocity_X*	*rightPalmVelocity_X*
	leftPalmVelocity_Y	*rightPalmVelocity_Y*
	leftPalmVelocity_Z	*rightPalmVelocity_Z*
Normal Vector	*leftPalmNormal_X*	*rightPalmNormal_X*
	leftPalmNormal_Y	*rightPalmNormal_Y*
	leftPalmNormal_Z	*rightPalmNormal_Z*

Table 5. List of raw variables obtained from the developed software.

4.3.1 Exercise 1. Wrist Flexo – Extension

The angle of maximum wrist flexion will be the parameter of interest for this exercise. The centre of palm of the hand movement is studied, in particular the unit vector normal to the palm of the hand, obtained by the variable 'PalmNormal', is processed to get this parameter. The normal vector is divided into its (x, y, z) components, with values ranging from -1 to 1 and according to the coordinate system of the device, the palms are fully stretched when the value of the z-component is 0, furthermore, a perfectly horizontal position would be given by values of the z and y components of 0 and -1 respectively. The z-component will take higher values as the wrist flexes and lower values as the wrist extends, so it will be used as a reference to calculate the highest and lowest points the wrist reaches. However, for the final calculation of the parameter, the three components will be used for a more rigorous computation, taking into account the possible deviations that may appear when performing the exercise.

First, the maxima and minima associated with the z component of the normal vector to the palm are sought for both hands (see Figure 42).

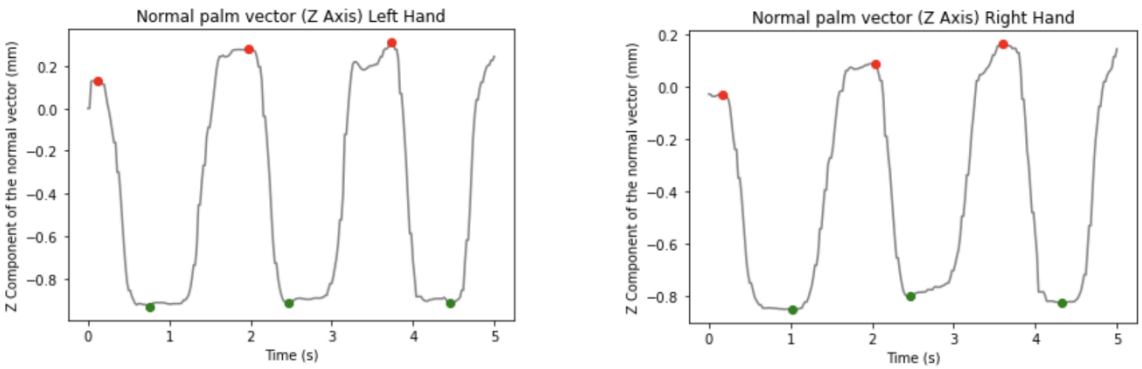


Figure 42 Normal palm vector. Z component. Exercise 1 a) Left hand b) Right hand

These maximum and minimum points are stored in an array, and the minimum value which corresponds to the maximum wrist flexion, and the maximum value which corresponds to the maximum wrist extension are selected. Components (x, y, z) associated with these points are stored in a new variable.

The maximum amplitude obtained in this exercise is therefore the angle between the two resulting vectors. As the parameter of interest will be the maximum angle from the horizontal, the starting point is forced to coincide with the horizontal. Therefore the values (0, -1, 0) are associated to the (x, y, z) components respectively and the angle with the point of maximum amplitude is calculated.

4.3.2 Exercise 2. Finger grip

Two factors are relevant to the gripper exercise: the subject's ability to successfully perform the gripper between thumb and forefinger and the form in which the exercise is achieved. For this purpose, the position of the tip of each finger is processed in two different analysis:

- Thumb and Index: The minimum and maximum Euclidean distance between the two fingers is calculated in the space domain. The minimum distance provides information on the subject's ability to close the gripper. In addition, the analysis in the X-Z plane (see Figure 43) will give information about the type of movement of each of the fingers to reach the gripper.

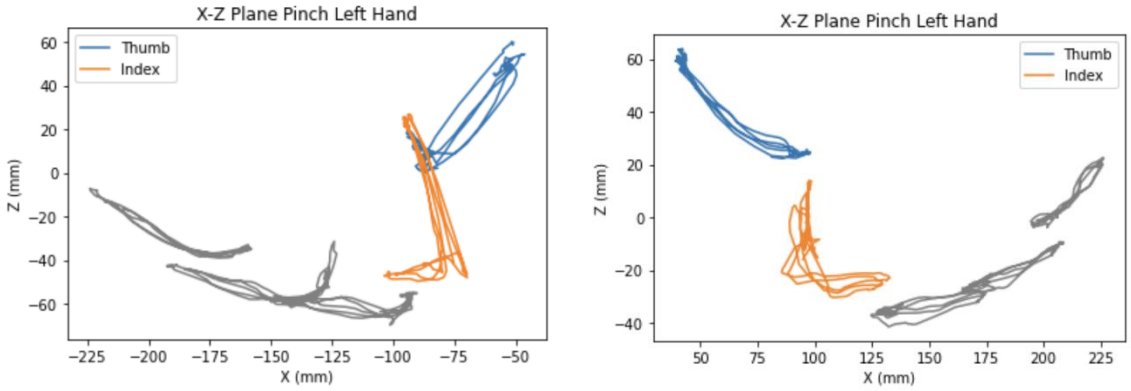


Figure 43 Exercise 2. X-Z plane fingers movement

- Middle, Ring and Pinkie: For these fingers, the movement they perform during the exercise is studied both in the plane and in space domain. During the test, the subject is asked to perform the gripper without

moving those three fingers, so the amount of movement really done by each finger to achieve the grip is studied.

For this purpose, the Convex Hull of each finger is calculated for the entire exercise. The convex hull of a set of points S in n dimensions can be defined as the intersection of all convex sets containing S. For N points p_1, ..., p_N, the convex hull C is then given by the expression (4.4) [60].

$$C \equiv \left\{ \sum_{j=1}^{N} \lambda_j p_j : \lambda_j \geq 0 \text{ for all } j \text{ and } \sum_{j=1}^{N} \lambda_j = 1 \right\} \tag{4.4}$$

This allows to calculate the total perimeter the area of movement of each fingertip studied in the X-Z plane (see Figure 44) and the total volume occupied by each fingertip during the exercise.

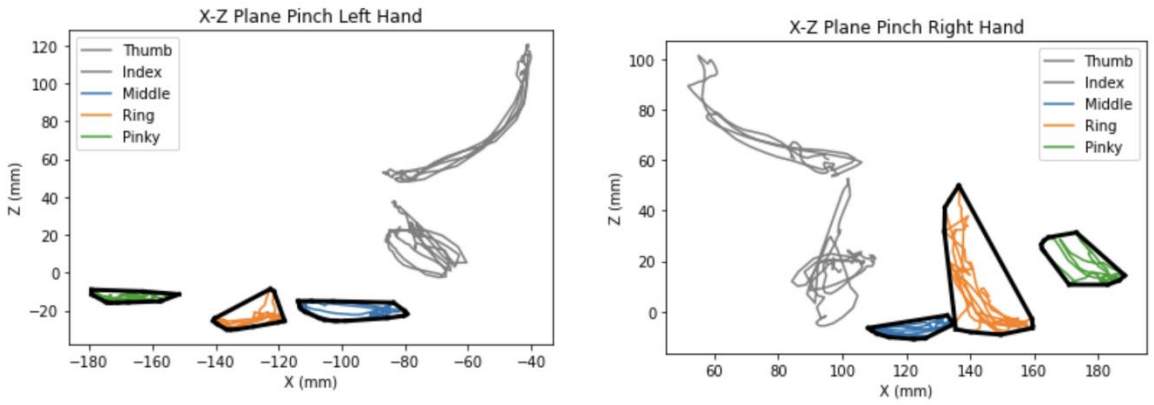


Figure 44 Exercise 2 Convex Hull

The list of variables obtained from this processing is shown in Table 6. However, only those highlighted will be used for further analysis in the validation process. This selection is based on the information provided by each of the parameters, volumes were discarded as they add a lot of variability.

PARAMETERS OBTAINED FOR EXERCISE 2

	Left Hand	Right Hand
Gripper Distances	**leftPinchDistMax**	**rightPinchDistMax**
	leftPinchDistMin	*rightPinchDistMin*
Finger Movements	**leftThumbRange**	**rightThumbRange**
	leftThumbRange3D	*rightThumbRange3D*
	leftThumbRange	*rightThumbRange*
	leftThumbRange3D	*rightThumbRange3D*
	leftThumbPerim	*rightThumbPerim*
	leftThumbArea2D	*rightThumbArea2D*
	leftThumbVolume	*rightThumbVolume*
	leftIndexRange	**rightIndexRange**
	leftIndexRange3D	*rightIndexRange3D*
	leftIndexPerim	*rightIndexPerim*
	leftIndexArea2D	*rightIndexArea2D*
	leftIndexVolume	*rightIndexVolume*
	leftMiddlePerim	**rightMiddlePerim**
	leftMiddleArea2D	*rightMiddleArea2D*
	leftMiddleVolume	*rightMiddleVolume*
	leftRingPerim	*rightRingPerim*
	leftRingArea2D	*rightRingArea2D*
	leftRingVolume	*rightRingVolume*
	leftPinkyPerim	*rightPinkyPerim*
	leftPinkyArea2D	*rightPinkyArea2D*
	leftPinkyVolume	*rightPinkyVolume*

Table 6. Variables obtained after processing raw data for exercise 2.

4.3.3 Exercise 3. Finger Separation

The processing of this exercise is carried out in the plane domain, since the entire exercise is performed in the x-z plane. Each of the fingertip positions is considered in order to determine the ranges of movement. Graphical representation of the movement can be seen in Figure 45.

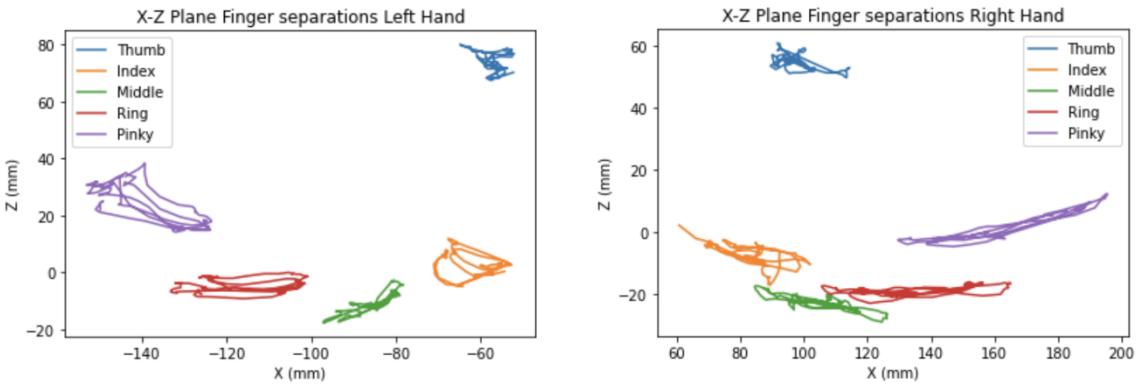


Figure 45 Exercise 3 X-Z plane Finger Separation

The maximum distances of the individual fingers are calculated to determine the range of movement. The list of variables obtained from this processing can be seen in Table 7. However, only those highlighted will be used for further analysis in the validation process. In this case just the middle finger range is omitted for the analysis as it is a finger that almost does not during the execution of this exercise.

PARAMETERS OBTAINED FOR EXERCISE 3

	Left Hand	Right Hand
Finger Movements	**leftThumbRange**	**rightThumbRange**
	leftIndexRange	**rightIndexRange**
	leftMiddleRange	*rightMiddleRange*
	leftRingRange	**rightRingRange**
	leftPinkyRange	**rightPinkyRange**

Table 7. Variables obtained from processing for Exercise 3.

4.3.4 Exercise 4. Fist Opening and Closure

For the analysis of the opening and closing of the fist, both the position in the x-z plane and in the domain of space are studied. As the tool aims to discriminate mild impairments, slight differences in performance are intended to be observed. Therefore the range of movement of each finger and the maximum and minimum perimeter in the x-z plane are calculated. In the space domain, the absolute maximum and minimum values of the volume of the Convex Hull of the values of the position of each fingertip

at each time instant. However, these last values will not be used for the validation, as they introduce high variability. Graphical representation of the movement can be seen in the figure below (see Figure 46).

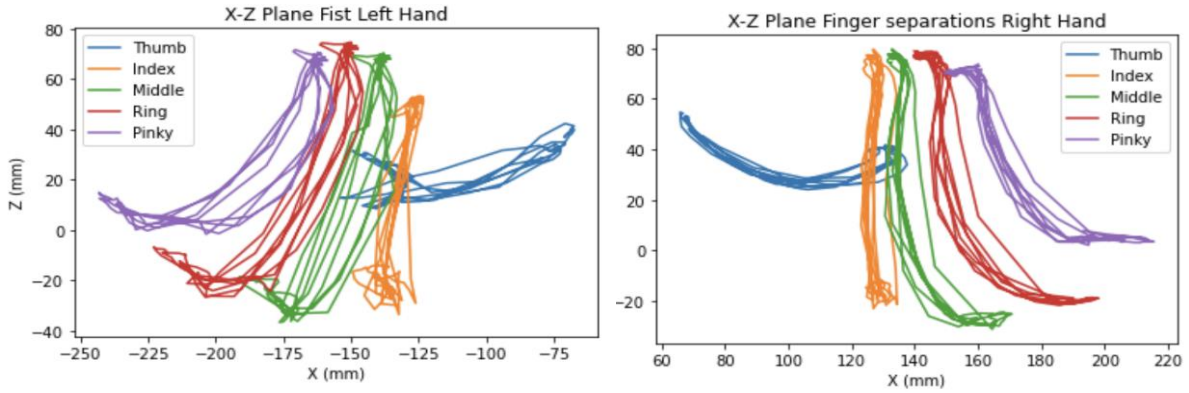


Figure 46 Exercise 4 X-Z plane Fist Opening and Closure

The Convex Hull associated with the maximum fist opening is expressed below (see Figure 47).

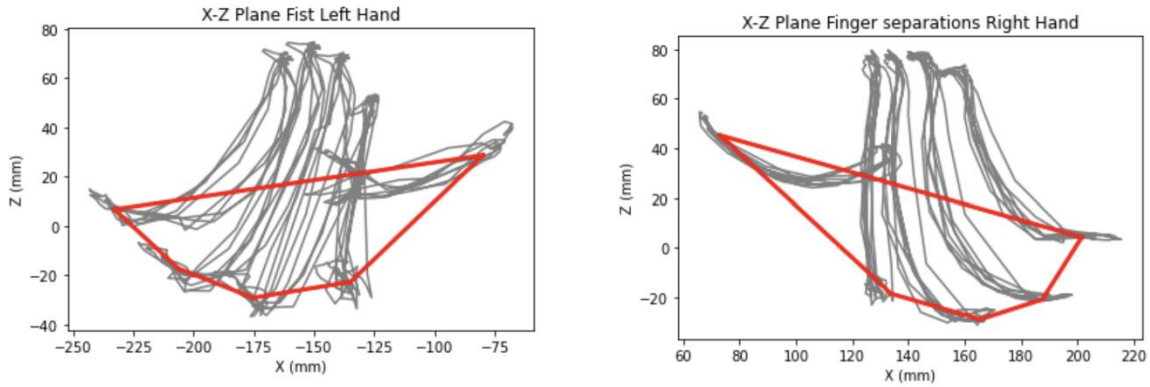


Figure 47 Exercise 4 Convex Hull associated with max opening

The list of variables obtained from this processing is shown in Table 8. However, only those highlighted will be used for further analysis in the validation process. The minimum perimeters were discarded as they do not provide relevant information as all of the users were able to close the fist, and parameters in the space domain were discarded as they generate a high variability.

PARAMETERS OBTAINED FOR EXERCISE 4

	Left Hand	Right Hand
Fist Convex Hull	**leftPerimMax**	**rightPerimMax**
	leftPerimMin	*rightPerimMin*
	leftArea2DMin	*rightArea2DMin*
	leftArea2DMax	*rightArea2DMax*
	leftVolumeMax	*rightVolumeMax*
	leftVolumeMin	*rightVolumeMin*
Finger Ranges	**leftThumbRange**	**rightThumbRange**
	leftThumbRange3D	*rightThumbRange3D*
	leftIndexRange	*rightIndexRange*
	leftIndexRange3D	*rightIndexRange3D*
	leftMiddleRange	*rightMiddleRange*
	leftMiddleRange3D	*rightMiddleRange3D*
	leftRingRange	*rightRingRange*
	leftRingRange3D	*rightRingRange3D*
	leftPinkyRange	*rightPinkyRange*
	leftPinkyRange3D	*rightPinkyRange3D*

Table 8. Variables obtained from processing for Exercise 4.

4.4 EUROQOL 5D. Calculation Tool Development

The calculation of the score assigned to the Euroqol 5D scale, as explained in Chapter 2, is very complex and therefore a complementary tool for automatic calculation has been developed. This consists on an executable software (see Figure 48), as a complementary tool to the main software for motion data tracking.

On the left-hand side of the form are each of the questions to be asked to the patient, with answers to which the values 1, 2 or 3 explained previously are assigned. The coefficients for the calculation of the final value are applied. The accept button will show the final result of the value. On the right side, the visual analogue scale is showed. The code used to develop the tool is presented in appendix A.

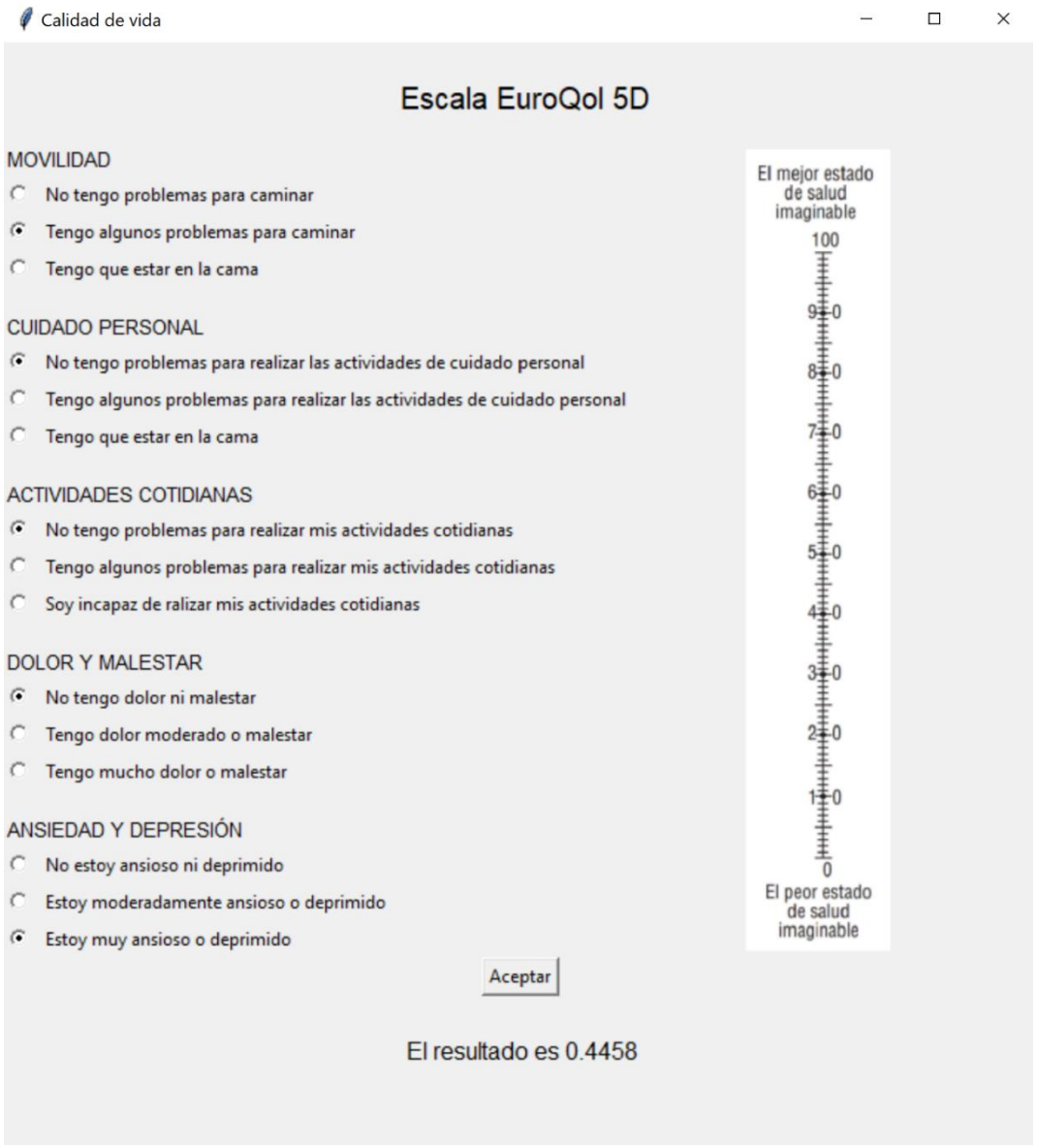


Figure 48 EuroQol 5D calculator interface. Own Elaboration.

4.5 CLINICAL VALIDATION STUDIES

The validation study of the tool consists of two phases:

- Case-control study: The tool is applied in healthy subjects (controls) and in acute stroke patients with functional hand deficits (cases) and the kinematic data obtained in the two groups is compared.

- Longitudinal observational study: In the stroke revision period, the study is repeated in patients to assess changes in kinematic data and correlate them with clinical evolution.

4.5.1 PATIENT / CONTROL RECRUITMENT AND EXCLUSION CRITERIA

Cases and controls were recruited in collaboration with the Department of Neurology and Stroke Centre of the 'Hospital Universitario La Paz', IdiPAZ. This process was conducted according to ethical standards of good clinical practice and to protection of personal data requirements, and with the authorisation of the Ethics and Biomedical Research Committee of the Hospital Universitario La Paz was obtained. All of the participants were volunteers that signed the provided informed consent. In addition, all the procedures of the study were carried out according to the rules established by the Law 14/2007 of 3 July on Biomedical Research and by the Regulation (EU) 2016/679 of the European Parliament and the Organic Law 3/2018 on the Protection of Personal Data and guarantee of digital rights.

The inclusion criteria for each of the groups are explained below:

- Patients: Clinically stable stroke patients with functional hand deficit present at the time of assessment who give signed consent to participate.

- Controls: Volunteers of similar age to the cases with no history of stroke or hand motor impairment who give their signed informed consent to participate.

The exclusion criteria that allow for a homogeneous and valid sample for statistical analysis are as follows:

- Aphasia or cognitive impairment, confusional syndrome, or other clinical situation that prevents understanding and performance of the task.

- Plegia or severe paresis of the upper limb that prevents performing the task.
- Having previously suffered a stroke with sequelae that may prevent from an accurate recording of data.
- Previous dependency.
- Diagnosis of any other neurological or musculoskeletal disease that may affect hand movement.
- Life expectancy of less than three months.
- Conditions that prevent follow-up at three months.

4.5.2 DATABASE CONFORMATION

Subject´s demographics and clinical data were collected and managed using REDCap (Research Electronic Data Capture) tools hosted at IdiPAZ Health Research Institute. RedCap [61] is a secure web application for building and managing databases, it is specifically geared to support online and offline data capture for research studies and operations.

The database contains a total of sixty-five variables which are divided into four main groups:

- **Demographic data and personal background**

  - Record ID. Consecutive numbers introduced by default by the proper RedCap tool, which indicate the order in the DataBase.
  - Patient ID. Unique identifier consisting of the subject code (Identifier introduced at the moment of the test, P for patients and C for controls) followed by the last 4 numbers of the medical record e.g. P14325. This allows the pseudo-anonymisation of the patient. The identification data are kept in a separate file held by the research team.

- Date of the study. DD-MM-YYYY
- Age. Integer e.g. 90
- Gender. Female (0), Male (1)
- Dominant Hand. Left-Handed (0), Right-Handed (1), Ambidextrous (2)
- Smoking. No (0), Yes (1), Former Smoker (2)
- Alcohol. No (0), Moderate (1), > 100 ml/day (2)
- Arterial hypertension. No (0), Yes (1)
- Diabetes. No (0), Yes (1)
- Dyslipidemia. No (0), Yes (1)
- Previous history of stroke. No (0), Yes (1)
    - Previous stroke location. Unknown (0), MCA territory (1), ACA territory (2), PCA territory (3), Basal Ganglia (4), Cerebellum (5), Brainstem (6)
    - Previous Lesion Side. Left (0), Right (1), Undetermined (2)
    - Affected Side. Left (0), Right (1), Bilateral (2), None (3)
    - Upper Limb Sequelae. No (0), Yes (1)

- **Clinical Data**

- Onset of Symptoms Date. DD-MM-YYYY
- Diagnosis. Transient ischemic attack (0), Territorial Cerebral Infarction (1), Lacunar Cerebral Infarction (2), Cerebral Haemorrhage (3).

- Location of lesion. Unknown (0), MCA territory (1), ACA territory (2), PCA territory (3), Basal Ganglia (4), Cerebellum (5), Brainstem (6)
- Symptomatic Side. Left (0), Right (1), Bilateral (2), None (3)
- Volume of lesion in MRI. Integer (cm^3)

- **Neurological Examination Data**

- Modified Rankin Scale score. Range (0-6)
- NIHSS score. Range (0-42)
- Fugl Meyer. Hand Section (C) score. Range (0-14)
- MB Wrist extension symptomatic side. Range (0-5)
- MB Pinch symptomatic side. Range (0-5)
- MB Fist symptomatic side. Range (0-5)
- MB Finger separation symptomatic side. Range (0-5)
- MB Wrist extension asymptomatic side. Range (0-5)
- MB Pinch asymptomatic side. Range (0-5)
- MB Fist asymptomatic side. Range (0-5)
- MB Finger separation asymptomatic side. Range (0-5)
- Follow Up. No (0), Yes (1)

- **Follow Up data**

- Follow Up Date. DD-MM-YYYY
- Treatment Received. No (0), Yes (1)
- Modified Rankin Scale score. Range (0-6)

- NIHSS score. Range (0-42)
- Fugl Meyer score. Hand Section (C). Range (0-14)
- MB Wrist extension symptomatic side Follow Up. Range (0-5)
- MB Pinch symptomatic side Follow Up. Range (0-5)
- MB Fist symptomatic side Follow Up. Range (0-5)
- MB Finger separation symptomatic side Follow Up. Range (0-5)
- MB Wrist extension asymptomatic side Follow Up. Range (0-5)
- MB Pinch asymptomatic side Follow Up. Range (0-5)
- MB Fist asymptomatic side Follow Up. Range (0-5)
- MB Finger separation asymptomatic side Follow Up. Range (0-5)
- EuroQol 5D. No (0) Yes (1)
- Mobility. Range (1-3)
- Personal Care. Range (1-3)
- Daily Activities. Range (1-3)
- Pain / Discomfort. Range (1-3)
- Anxiety / Depression. Range (1-3)
- Health State Value. Range (-0.0757 - 1)
- Analogue Visual Scale. Range (0-100)

The database is stored and managed by the RedCap tool, and once all the data has been collected and reviewed, it will be exported to a .csv file that will be integrated with the kinematic parameters obtained from the subjects.

4.5.3 DATA ANALYSIS

This section discusses the different methods of analysis used in each of the studies, as well as the form in which the data obtained in this process are expressed.

The statistical analysis is performed using Python 3 [62]. The descriptive and comparative analysis is conducted considering the predefined group. Categorical variables are expressed as percentages and continuous variables are expressed as mean and standard deviation (SD) or median and interquartile ranges (IQR).

Case/Control Study

Comparisons between kinematic data from the control group and patients are carried out to determine the tools' ability to detect differences attributable to deficits associated with the stroke. First of all, the dominant and the non-dominant sides are compared among controls to find out if there are differences in performance related to dominancy. Subsequently, an analysis between controls and the symptomatic and non-symptomatic hands of the patients is carried out.

An Independent two sample t-test is performed, to compare controls and patients. The significance level (alpha) that allows to either reject or accept the alternative hypothesis is set at $p < 0.05$.

Longitudinal Study

For this study, only patients are analyzed, comparing the results in the acute phase and at follow-up. The acute symptomatic hand is compared with its respective symptomatic hand at follow-up and the acute asymptomatic hand is compared with its respective asymptomatic hand at the follow up using a paired t-test. The significance value is also set to $p < 0.05$.

In order to determine whether the tool is able to detect evolutionary changes in patients, a paired t-test is carried out. In this statistical procedure the null hypothesis assumes that the true mean difference between the paired samples is zero. On the contrary the alternative hypothesis assumes that the true mean difference between the paired samples is not equal to zero. The significance value is set to 0.05 as in the Case-

Control study and two more levels of significance ($p < 0.005$ and $p < 0.0005$) are also added for the same purpose.

Correlations

The correlations between kinematic variables and clinical scale scores are analysed using the Pearson's correlation coefficient.

Also, the correlations between the kinematic variables at follow up and Euroqol5D scores are analysed to find out if better kinematic values are related to a better quality of life in patients.

In addition, together with the correlation study, a best-fit regression line will be calculated for each of the two variables to be compared.

5 RESULTS

5.1 Case / Control Study

5.1.1 Clinical Data

Characteristics including demographics, clinical assessment and stroke diagnosis are summarized in Table 9. Ninety-three controls are recruited with a mean age of 49,63 ± 15,27 years, thirty-two are men, representing 34.4% of the total number of controls. Seventy-nine patients with acute stroke participated in the study, with higher age than controls 64,64 ± 14,39 vs 49,63 ± 15,27, ($p < 0.05$) and 49 out of these 79 patients (62,02 %) were men.

Patients present a median value of 1 in the NIHSS score, being 9 the maximum value and 0 the minimum and a median value of 13 in the FMA-UE (Hand Items) score with a range between 4 and 14, which implies that the sample is conformed of patients with mild to moderate deficit. Ten (12,66 %) patients are diagnosed with transient ischaemic attack, 47 (59,49 %) suffer from territorial cerebral infarction, 16 (20,25 %) from lacunar cerebral Infarction and 5 (6,33 %) from cerebral haemorrhage. The diagnosis of one patient is undetermined as no imaging studies were available at the moment of the inclusion.

The average time from stroke-onset to assessment in days is 17,02 ± 42,6. Moreover, the majority of the participants are right-handed except two left-handed controls and one ambidextrous patient.

Clinical Descriptive. Characteristics of the cases and controls

Variable	*Cases (n = 79)*	*Controls (n = 93)*
Age (years) (Mean +/- SD)	64.64 ± 14.39	49.63 ± 15.27
Sex: Male, N (%)	49 (62,02 %)	32 (34,40 %)
Clinical Assessment		
NIHSS score, median (range)	1, (0 - 9)	----
Fugl-Meyer-UE (hand ítems) score, median (range)	13, (4 - 14)	----
Stroke Subtype		
TIA, N (%)	10 (12,66%)	----
Territorial cerebral infarction, N (%)	47 (59,49%)	----
Lacunar cerebral infarction, N (%)	16 (20,25%)	----
Cerebral haemorrhage, N (%)	5 (6,33%)	----
Unknown, N (%)	1 (1,27%)	----
Time from stroke-onset to assessment		
time-lapse stroke-study (days), mean (+/-SD)	17.02 ± 42.6	----

Table 9. Clinical descriptive of the sample.

5.1.2 Normality values of selected parameters in control subjects

First, an analysis is carried out on the control group to determine the normality values for each parameter studied and to find out if there are differences between the dominant and non-dominant side (see Table 10). In addition, the distributions of each of the parameters are observed to check whether they follow normal distributions.

These normality values are calculated with the objective of establishing ranges in which the movement is considered normal, and thus to have a threshold to identify values below that range as a deficit of movement.

Table of normality values of selected parameters

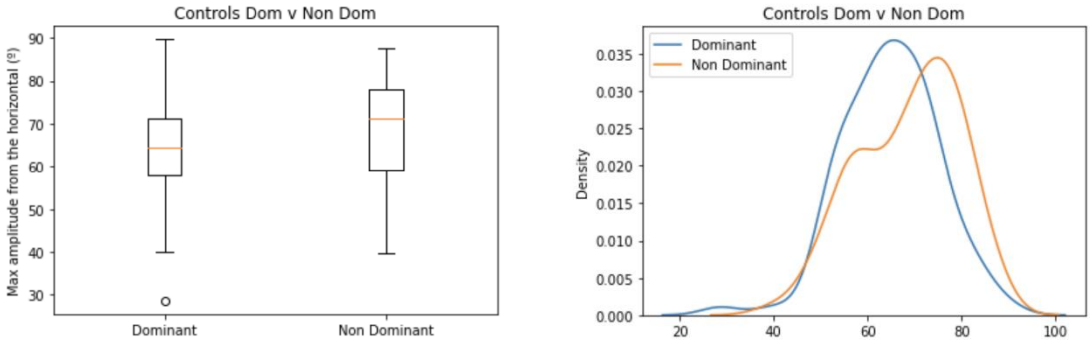
	Dominant	Non Dominant	p-value
1. Wrist. Flexo - Extension			
1.1 Amplitude from the horizontal plane (º)	64.826 ± 10.076	68.648 ± 10.766	0.0148
2. Finger grip			
2.1 Max Grip Distance (mm)	111.632 ± 17.662	112.771 ± 17.869	0.6702
2.2 Thumb Range (mm)	49.053 ± 19.533	51.303 ± 21.077	0.4636
2.3 Index Range (mm)	64.650 ± 21.282	66.438 ± 23.551	0.5979
2.4 Ring Perimeter (mm)	90.060 ± 46.353	94.781 ± 51.137	0.5219
3. Finger Separation			
3.1 Thumb Range (mm)	61.144 ± 21.049	63.969 ± 21.560	0.3830
3.2 Index Range (mm)	43.829 ± 20.100	45.443 ± 18.346	0.5809
3.3 Ring Range (mm)	75.721 ± 25.312	79.221 ± 25.040	0.3605
3.4 Pinky Range (mm)	78.889 ± 17.707	90.654 ± 24.139	0.0002
4. Fist. Open and closure			
4.1 Max Perimeter (mm)	382.180 ± 39.204	383.170 ± 42.510	0.8732
4.2 Thumb Range(mm)	77.481 ± 23.189	77.759 ± 21.862	0.9356

Table 10. Table of normality values of selected parameters.

All parameters follow normal distributions (see Figure 49 to Figure 59), and are very similar between dominant and non-dominant side, thus confirming non significant difference in performance depending on dominance.

The only parameters that show some differences are ‘Amplitude from the horizontal plane’ from exercise 1 and ‘Pinky Range’ from exercise 3, but as these differences do not affect in the final outcomes of the validation study (see Section 5.1.4), they are not considered. Therefore, dominance is not taken into account as a variable that could affect the performance of the exercises.

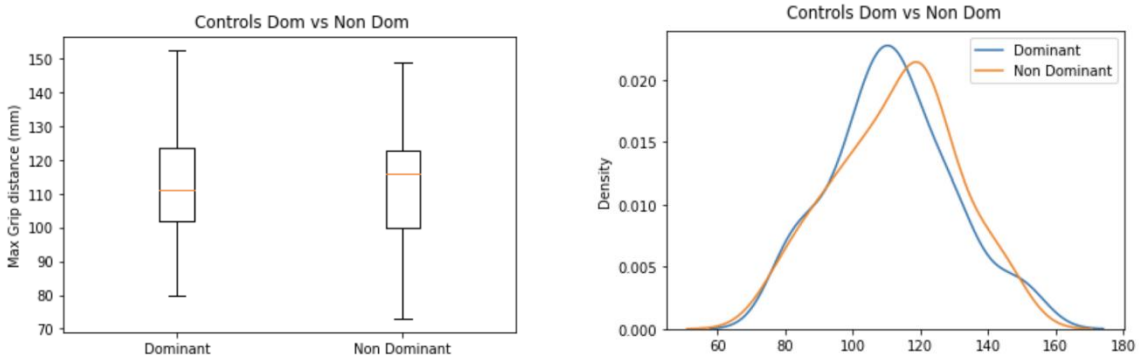
- **Wrist Flexo-Extension exercise**
  - Max Amplitude from the horizontal



a) b)

Figure 49 Exercise 1. Max amplitude from the horizontal Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

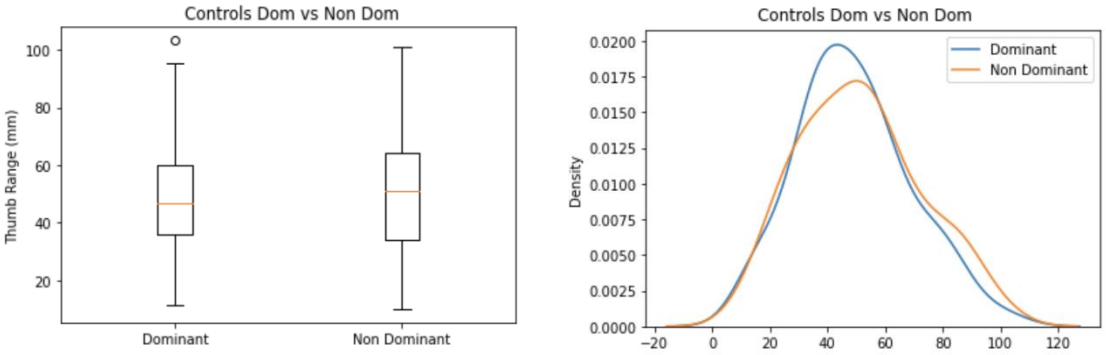
- **Finger Grip exercise**
  - Maximum Grip distance



a) b)

Figure 50 Exercise 2. Max grip distance Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

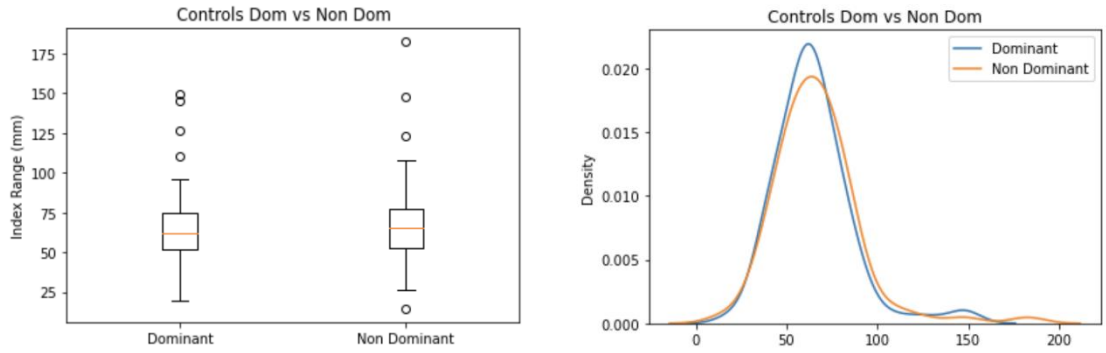
- Thumb Range



a) b)

Figure 51 Exercise 2. Thumb Range Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

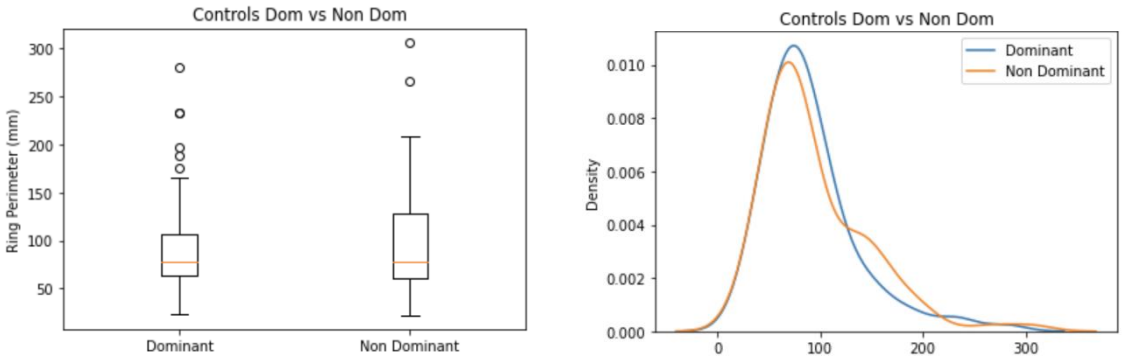
- Index Range



a) b)

Figure 52 Exercise 2. Index Range Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

- Ring Perimeter

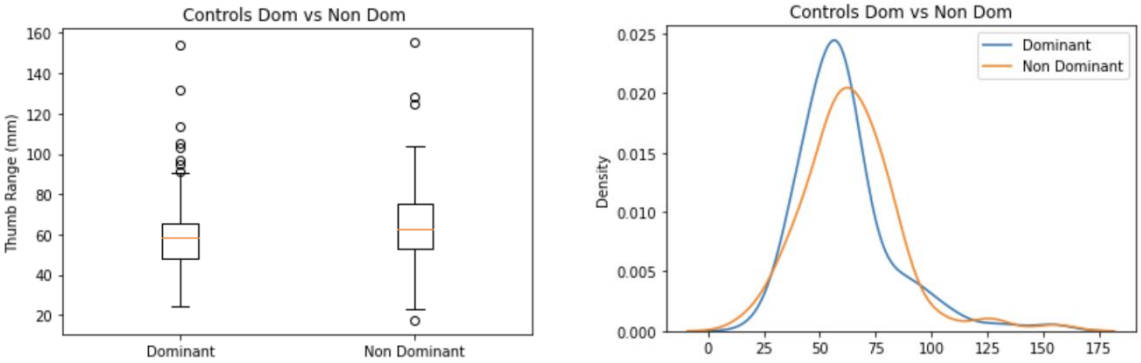


a) b)

Figure 53 Exercise 2. Ring Perimeter Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

- **Finger Separation exercise**

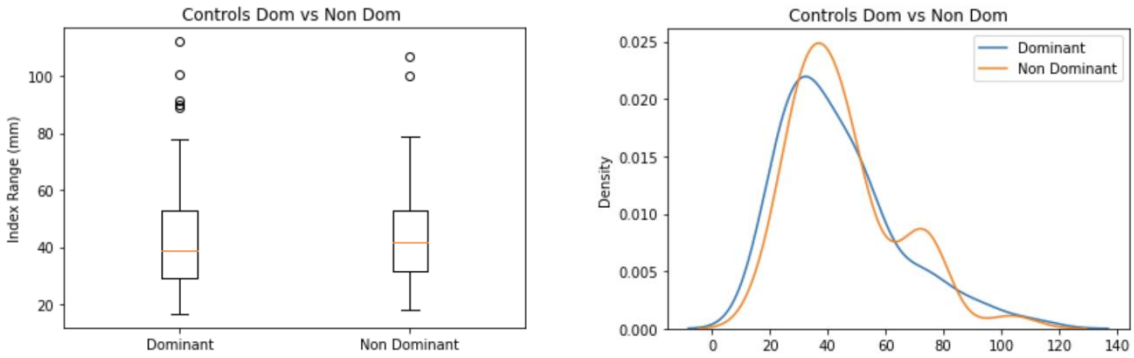
  - Thumb Range



a) b)

Figure 54 Exercise 3. Thumb Range Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

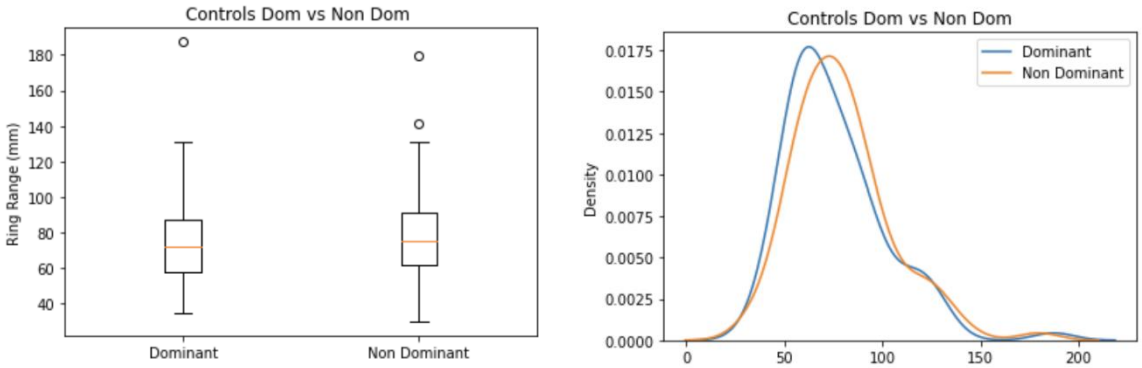
- Index Range



a) b)

Figure 55 Exercise 3. Index Range Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

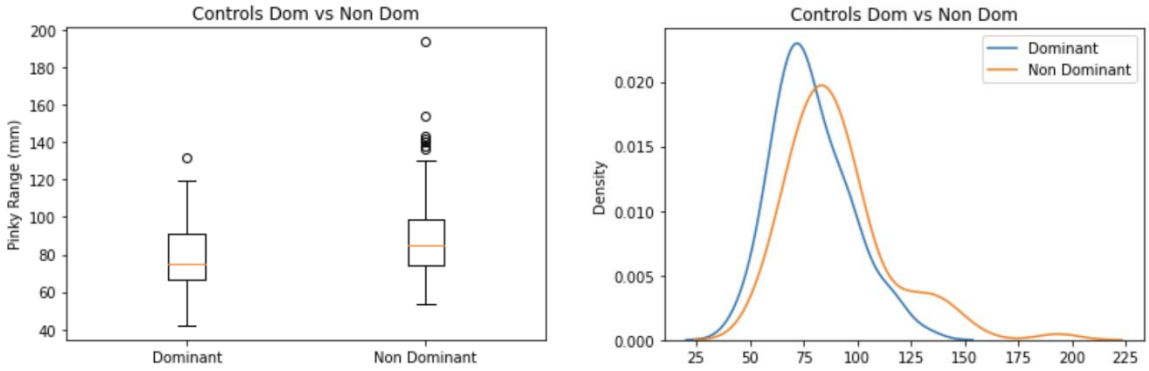
- Ring Range



a) b)

Figure 56 Exercise 3. Ring Range Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

- Pinky Range

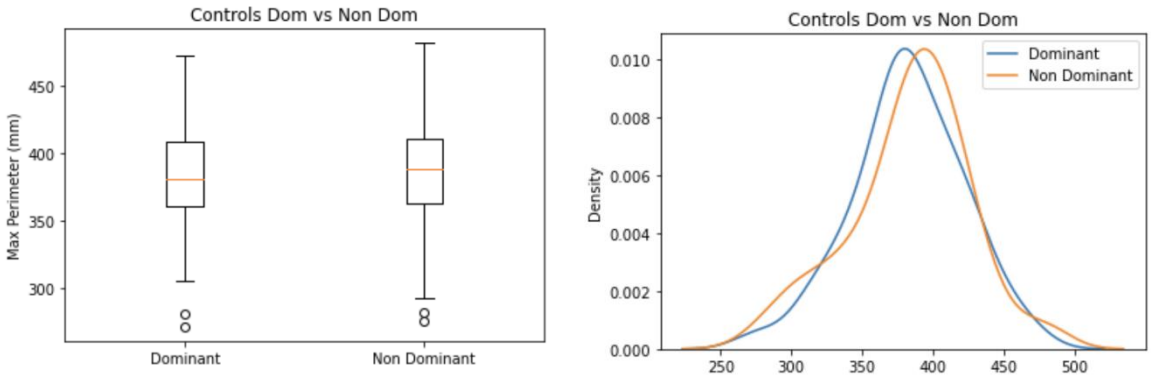


a) b)

Figure 57 Exercise 3. Pinky Range Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

- **Fist Opening and closure**

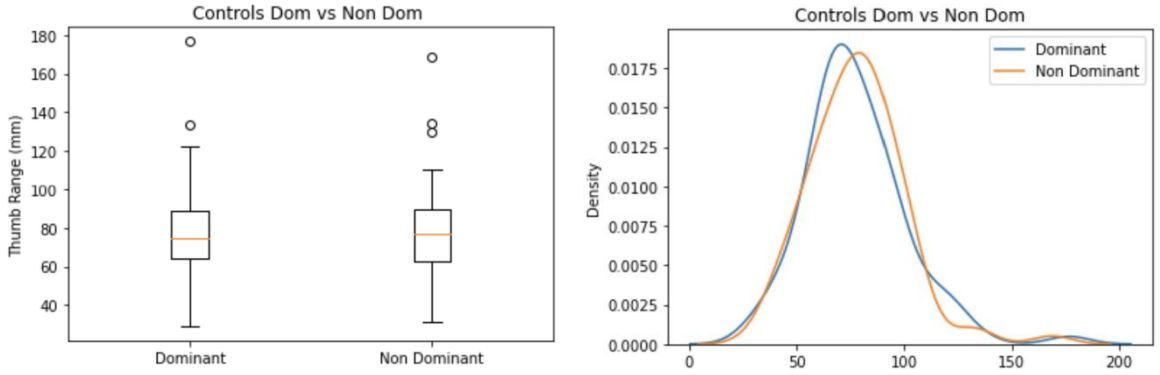
  - Max Perimeter



a) b)

Figure 58 Exercise 4. Max Perimeter Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

- Thumb Range



a) b)

Figure 59 Exercise 4. Thumb Range Control Dominant Side vs Non-Dominant Side a) Box Plot b) Density Plots.

5.1.3 Analysis of the relation between kinematic parameters and age

During data collection, an attempt was made to maintain age equity between patients and controls. However, the age of the inpatients is significantly higher than that of the controls, as age is one of the risk factors for stroke, and most of the controls are volunteers working in the hospital who do not reach such a high age.

Considering that age may influence movement quality to explore whether the difference in age between cases and controls may have an impact on the results, correlation between age and each of the kinematic parameters of interest, is carried out.

The results of this analysis are shown in the correlation matrix below (see Figure 60). This matrix is computed using the Pearson´s correlation test (Pearson's r). In addition, a graphical representation of each correlation analysis is showed, including the best regression line that fits that correlation. (see Figure 61 Figure 62 to Figure 64). In order to differentiate the same measures for different exercises in the matrix, the code of each exercise (Ex + Number of exercise) has been added at the end of the name of each variable.

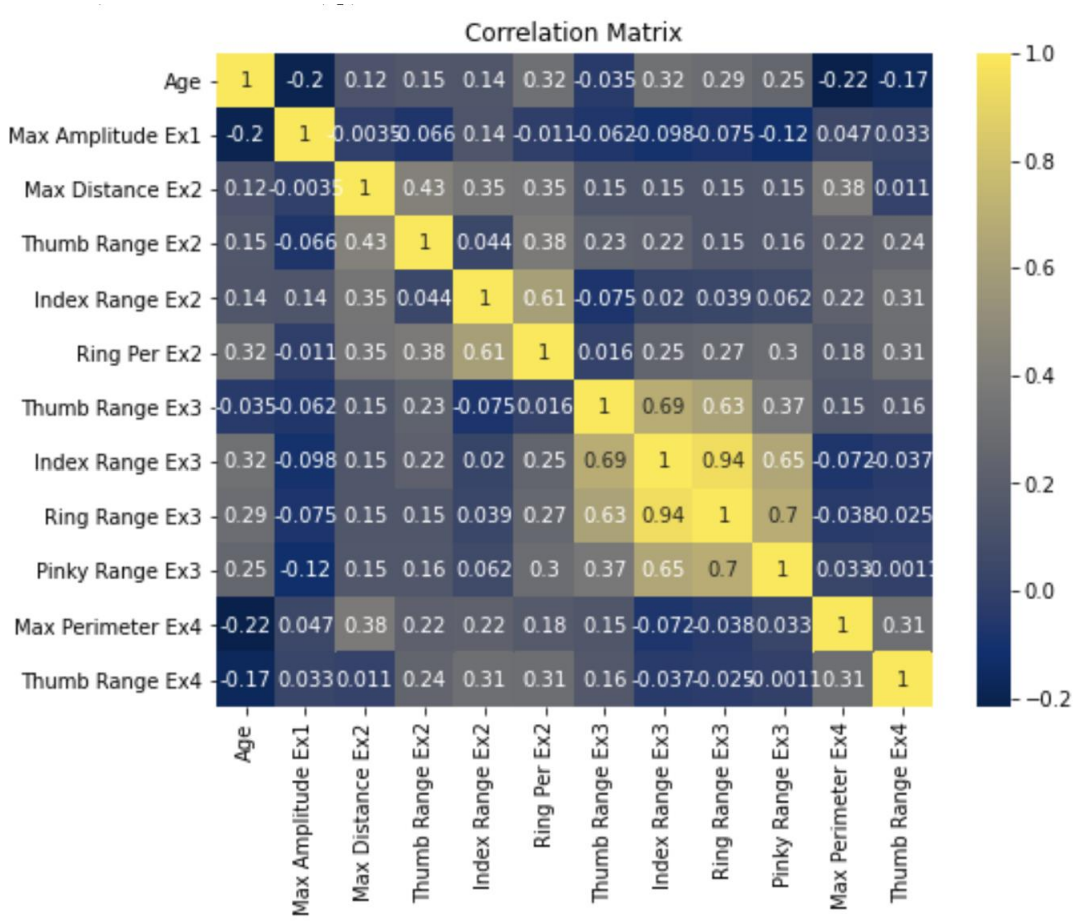


Figure 60 Correlation Matrix of the selected parameters and the Age

- **Wrist Flexo-Extension exercise**

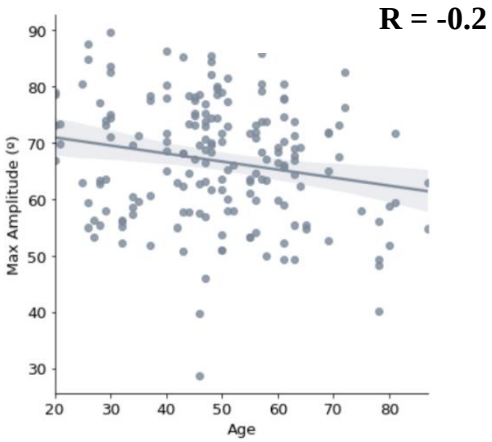


Figure 61 Correlation between Age and Max Amplitude from the horizontal.

- **Finger Grip exercise**

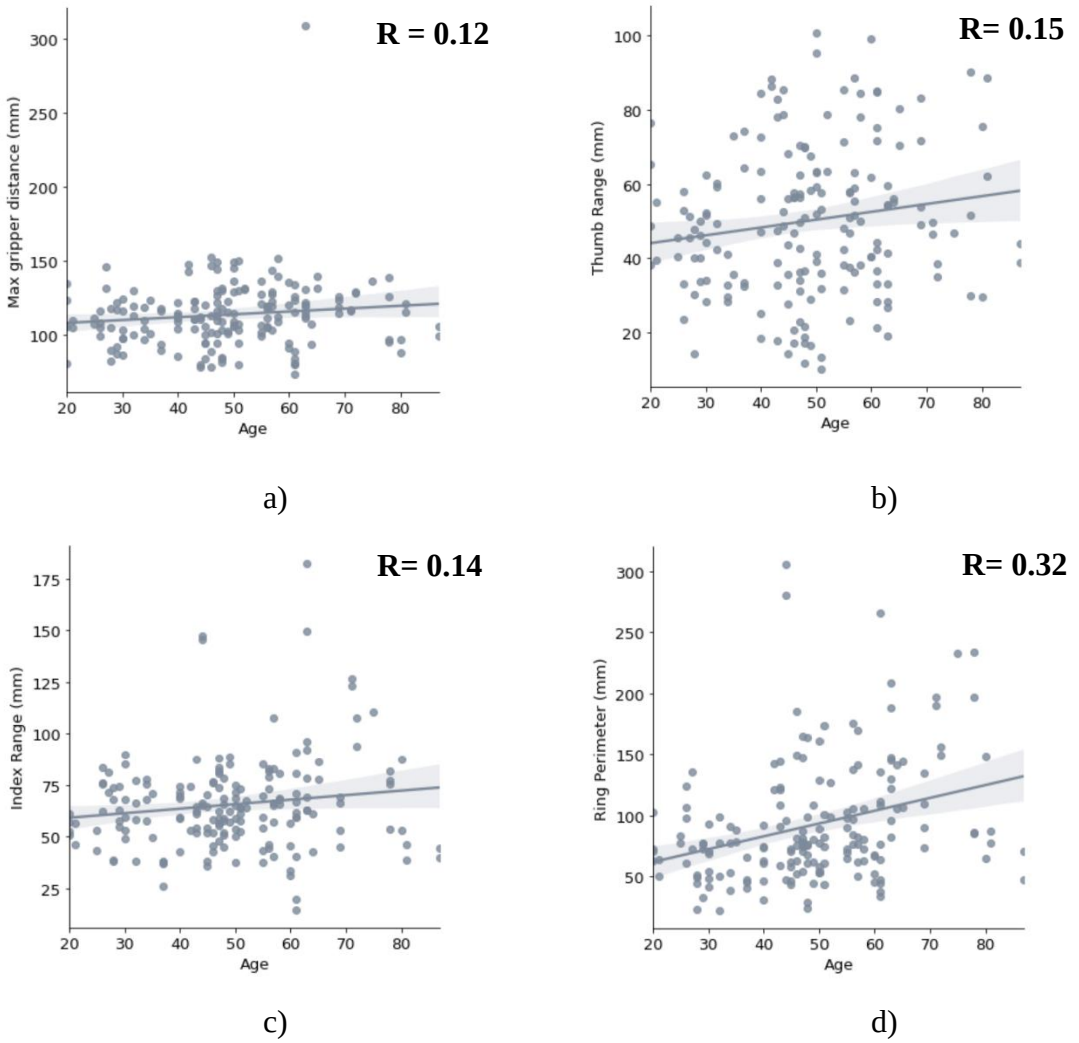


Figure 62. a) Correlation between Age and Max Gripper distance, b) Correlation between Age and Thumb Range, c) Correlation between Age and Index Range, d) Correlation between Age and Ring Perimeter.

- **Finger Separation exercise**

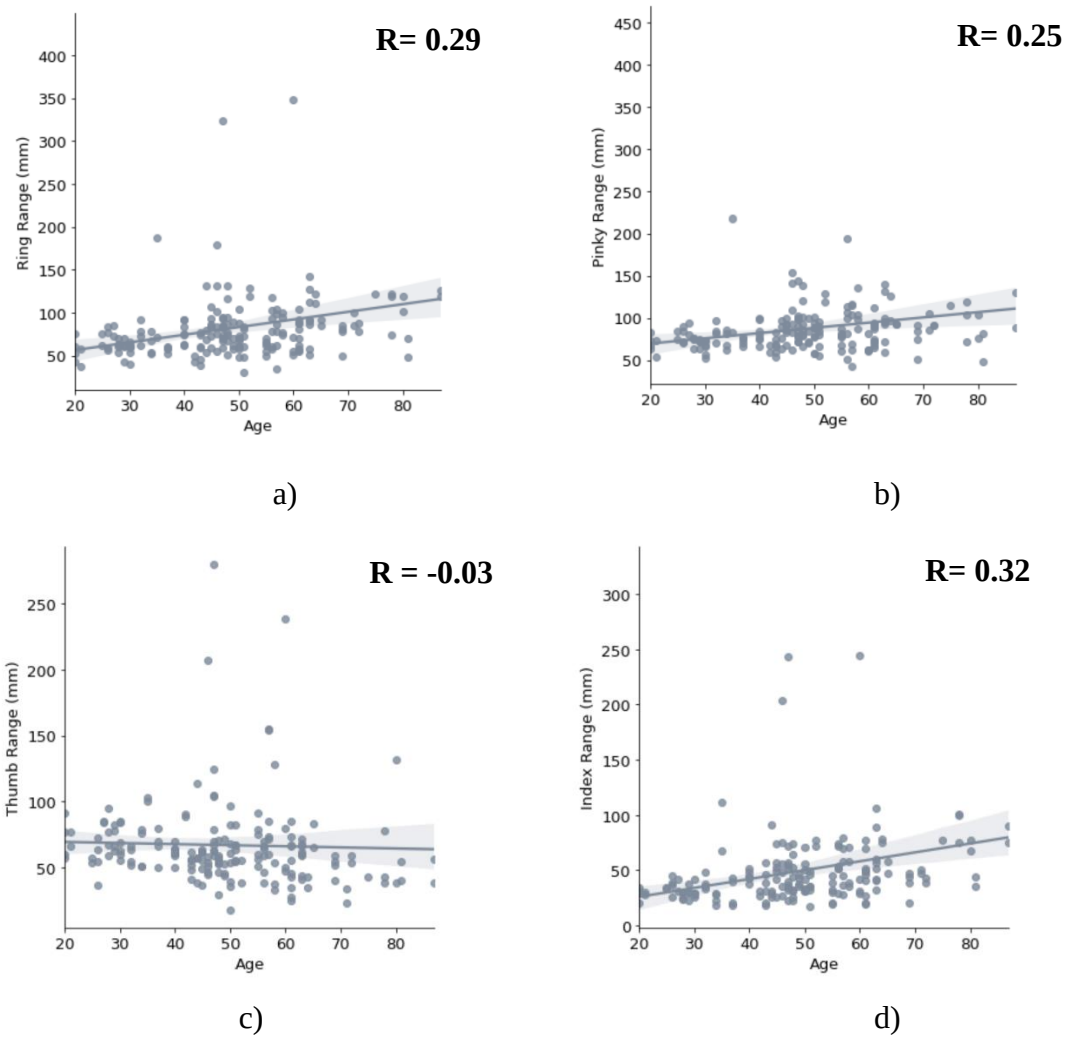
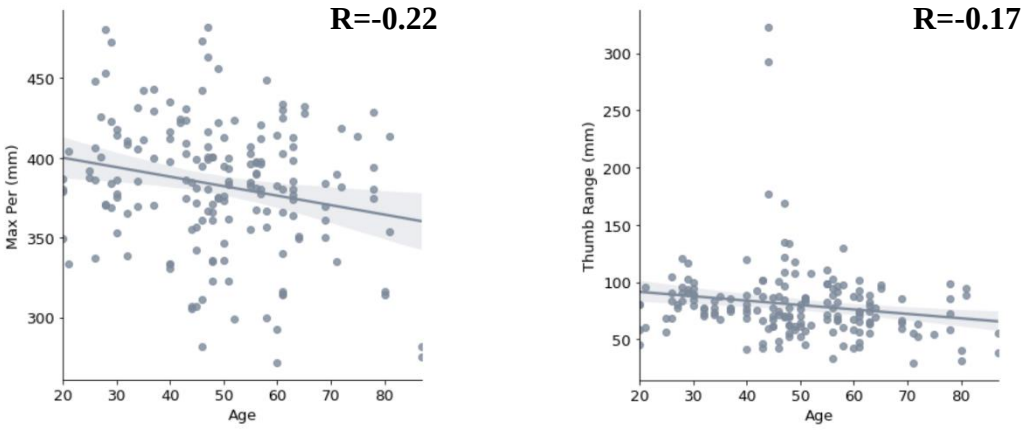


Figure 63. a) Correlation between Age and Thumb Range, b) Correlation between Age and Index Range, c) Correlation between Age and Ring Range, d) Correlation between Age and Pinky Range.

- **Fist Opening and Closure exercise**



a) b)

Figure 64. a) Correlation between Age and Max Perimeter, b) Correlation between Age and Thumb Range.

There was a great dispersion of results and there were no significant correlations between age and any of the parameters being the highest coefficient 0.32 found in the parameters ‘Ring Perimeter Ex2’ and 'Index Range Ex3'.

Since there is no correlation with age, it is considered that age is not significantly affecting the results and that it would not account for any difference between cases and controls.

5.1.4 Comparison of kinematic data between patients and controls

A first test is carried out in which the asymptomatic hand of the patients is compared with the symptomatic hand and both with those of controls. For the analysis, both hands of controls are grouped together as the absence of differences between the dominant and non-dominant side was previously demonstrated. This test allows to verify the tool's ability to discriminate the deficit of the affected hand in cases.

Subsequently, a more specific to assess if the degree of impairment may vary according to whether the symptomatic hand is dominant or not is performed. For that

purpose the symptomatic dominant and non-dominant hands of the patients are introduced to see whether, although in controls there are no differences between dominant and non-dominant hands and the asymptomatic dominant and non-dominant hands of the patients are compared.

The main findings for every parameter of each exercise are summarized and the graphical representation of the mentioned comparisons are shown (see Figure 65 to Figure 75), as well as the p-values for each comparison (see Table 11 to Table 21). All variables followed a normal distribution.

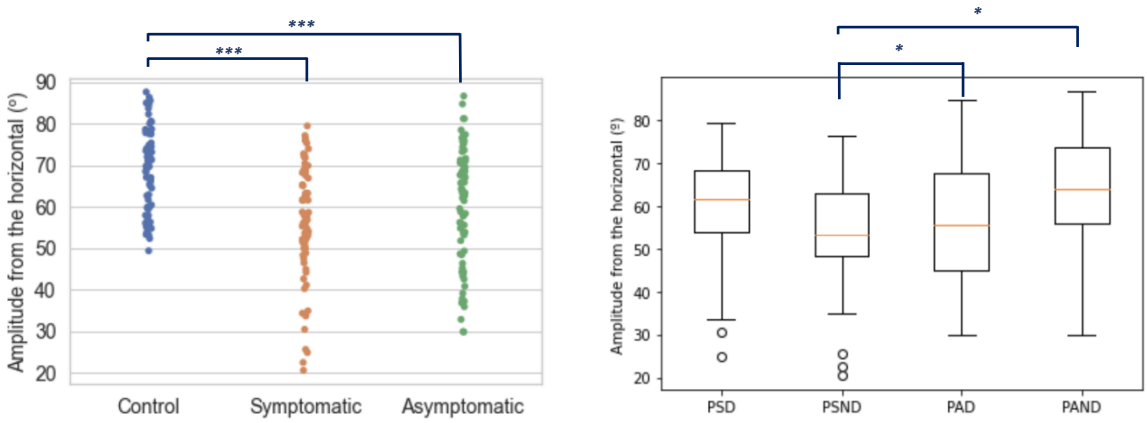
For the boxplots made, the following abbreviations are used:

- PSD: Patient Symptomatic Dominant
- PSND: Patient Symptomatic Non-Dominant
- PAD: Patient Asymptomatic Non-Dominant
- PAND: Patient Asymptomatic Non-Dominant

Controls are represented in blue, the symptomatic side of the patients is represented in orange and the asymptomatic side of the patients in green.

- **Wrist Flexo – Extension exercise**
  - Amplitude from the horizontal

The parameter 'Amplitude from horizontal' in exercise 1 is one of the most discriminating among all selected (see Table 11). Statistically significant differences between controls and patients are found in both symptomatic ($p = 6.62$ e-10) and asymptomatic ($p = 3.82$ e-10) hands, this suggests that the theoretically healthy hand may have been affected also by this disease. This is reinforced by the fact that no statistically significant differences are found between the symptomatic and asymptomatic side of the patients. A greater dispersion in the data can be observed in the patients (which probably reflects variable degree of deficits, while the results of the controls are more clustered, none of them being below 50° (see Figure 65).



a) b)

Figure 65 Amplitude from the horizontal Control and Patients.

Results of the independent sample t-test

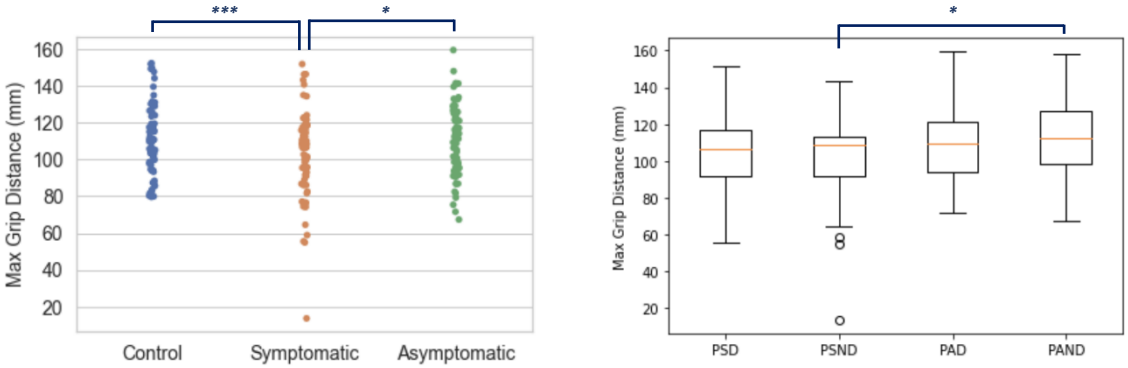
Variable	p-value
Control vs Patient Symptomatic	**6.62 e-10**
Control vs Patient Asymptomatic	**3.82 e-5**
Patient Symptomatic vs Patient Asymptomatic	0.136
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.137
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.498
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.182
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	**0.044**
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	**0.009**

Table 11. Results of the independent sample t-test. P-values for the Amplitude from the horizontal parameter. *p<0.05, **p<0.005, ***p<0.0005.

- **Finger Grip exercise**
  - Maximum Grip Distance

Statistically significant differences (p = 8.1 e-3) between the controls and the symptomatic side of the patients are found for the 'Maximum Grip Distance' parameter of exercise 2 (see Table 12). These results indicate that the affected hand of the patients is not fully able to open the index thumb gripper. In this case there are no differences

between controls and the asymptomatic hand of the patients, and there are differences between the symptomatic and non-symptomatic sides of the patients (p = 0.004). The distributions indicate that the controls and the asymptomatic side have similar values while the symptomatic side has lower values (see Figure 66).



a) b)

Figure 66. Max Grip Distance a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

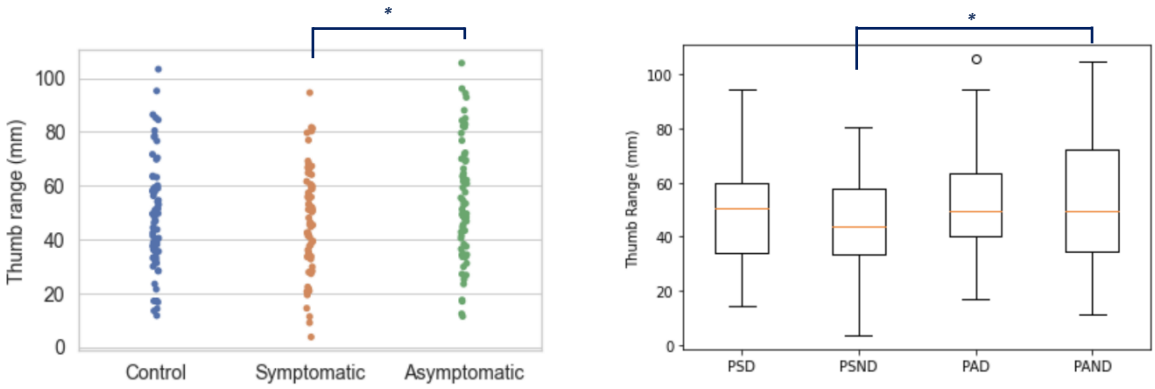
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	**8.1 e-3**
Control vs Patient Asymptomatic	0.641
Patient Symptomatic vs Patient Asymptomatic	**0.026**
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.485
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.464
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.078
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.179
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	**0.023**

Table 12. Results of the independent sample t-test. P-values for the Maximum Grip distance parameter. *p<0.05, **p<0.005, ***p<0.0005.

- Thumb Range

Regarding the parameter 'Thumb range' it can be observed that it is a much less discriminating parameter (see Table 13). Only mild differences can be found between symptomatic and asymptomatic hands of patients, and values for controls and both patient sides are very similar (See Figure 67). This suggests that the problem that patients are not able to fully open the gripper is not due to the movement of the thumb.



a) b)

Figure 67. Thumb Range a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

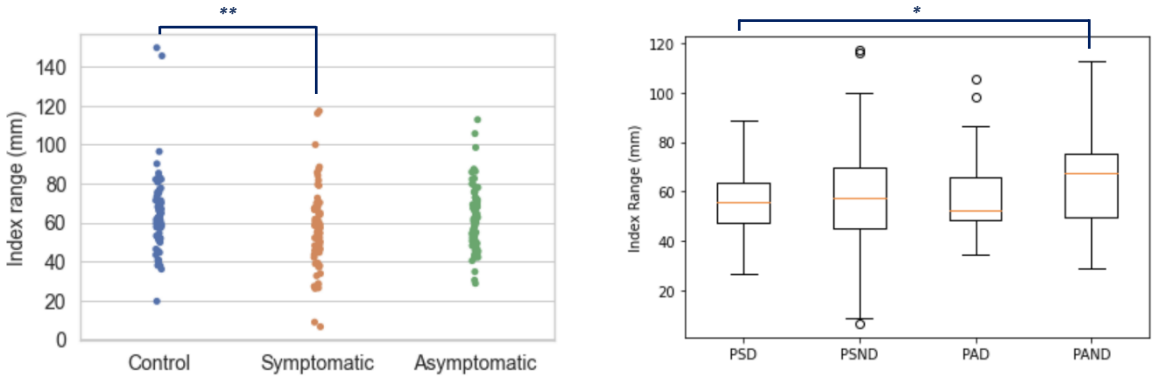
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	0.268
Control vs Patient Asymptomatic	0.192
Patient Symptomatic vs Patient Asymptomatic	**0.047**
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.326
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.392
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.254
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.090
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	**0.054**

Table 13. Results of the independent sample t-test. P-values for the Thumb Range parameter. *p<0.05, **p<0.005, ***p<0.0005.

- Index Range

Statistically significant differences between controls and the symptomatic hand of patients are found (see Table 14) for the parameter 'Index range' ($p = 0.005$). These differences appear mainly on the dominant side as there are also statistically significant differences between the symptomatic hand of patients and controls on the dominant sides ($p = 0.019$). These results indicate that the movement of the index finger has a significant influence on achieving a full opening when performing the gripper. As for the distributions (see Figure 68), the values of the symptomatic side of the patients are more dispersed, whereas the values of the controls are close to those of the asymptomatic side of the patients.



a) b)

Figure 68. Index Range a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

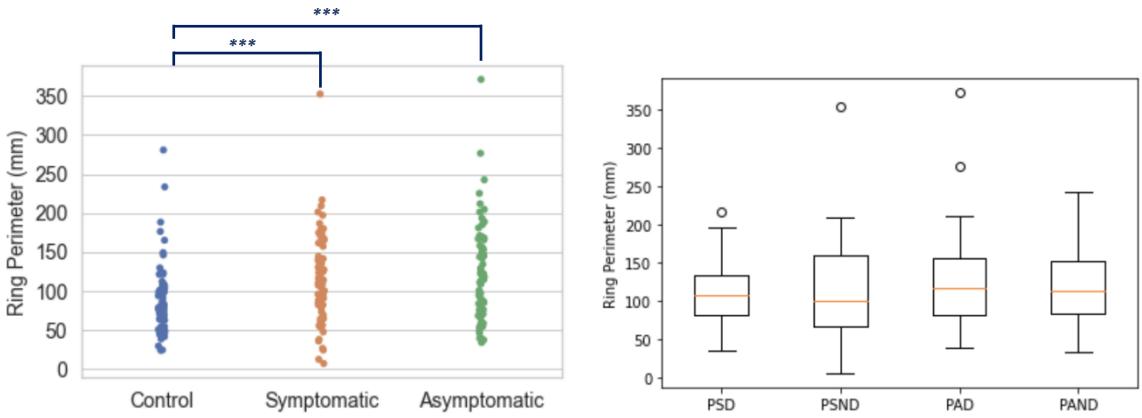
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	**0.005**
Control vs Patient Asymptomatic	0.201
Patient Symptomatic vs Patient Asymptomatic	0.134
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.533
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.443
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	**0.022**
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.986
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	0.253

Table 14. Results of the independent sample t-test. P-values for the Index Range parameter. *p<0.05, **p<0.005, ***p<0.0005.

- Ring Perimeter

The parameter 'Ring perimeter' provides valuable information about how exercise 2 is performed. Statistically significant differences are found between controls and the symptomatic (p = 0.007) and non-symptomatic (p = 4.8 e-4) sides of the patients (see Table 15). These results indicate that patients need more movement in the fingers not involved in the gripper to be able to close and open it successfully. Regarding the distributions of the values (see Figure 69), it is striking that the asymptomatic hand shows higher values than the symptomatic hand, although this may be due to the loss of mobility on the affected side.



a) b)

Figure 69. Ring Perimeter a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

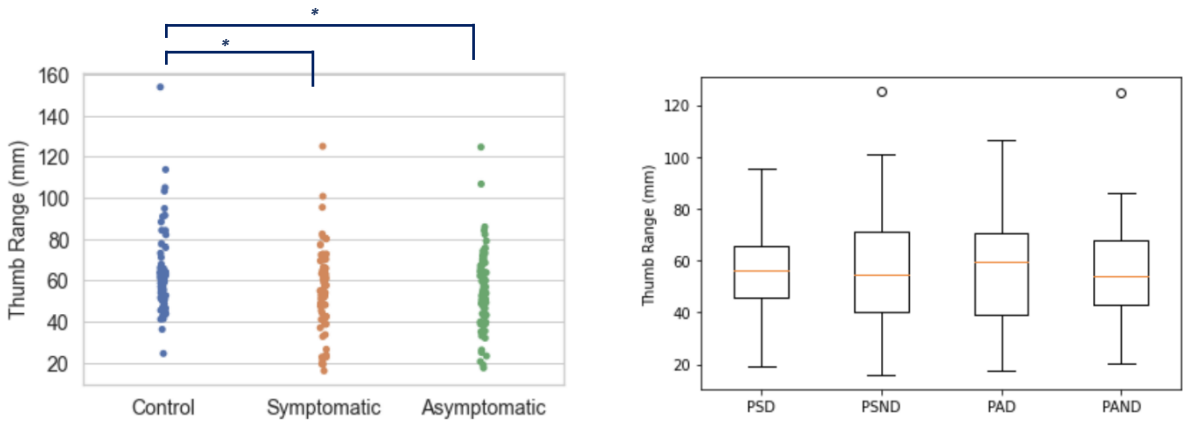
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	**0.007**
Control vs Patient Asymptomatic	**4.8 e-4**
Patient Symptomatic vs Patient Asymptomatic	0.275
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.805
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.200
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.471
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.417
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	0.757

Table 15. Results of the independent sample t-test. P-values for the Ring Perimeter parameter. *p<0.05, **p<0.005, ***p<0.0005.

- **Finger Separation exercise**
    - Thumb Range

Exercise 3 is one of the least discriminating, but the tool is able to capture the movement very accurately due to the position of the hands in relation to the camera. For the range of the thumb, statistically significant, although mild differences are found between controls and symptomatic (p = 0.017) and non-symptomatic (p = 0.025) sides of the patients (see Table 16). For this parameter no differences are found between symptomatic and asymptomatic sides of the patients, which indicates that the theoretically unaffected side is actually presenting deficit.



a) b)

Figure 70. Thumb Range a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

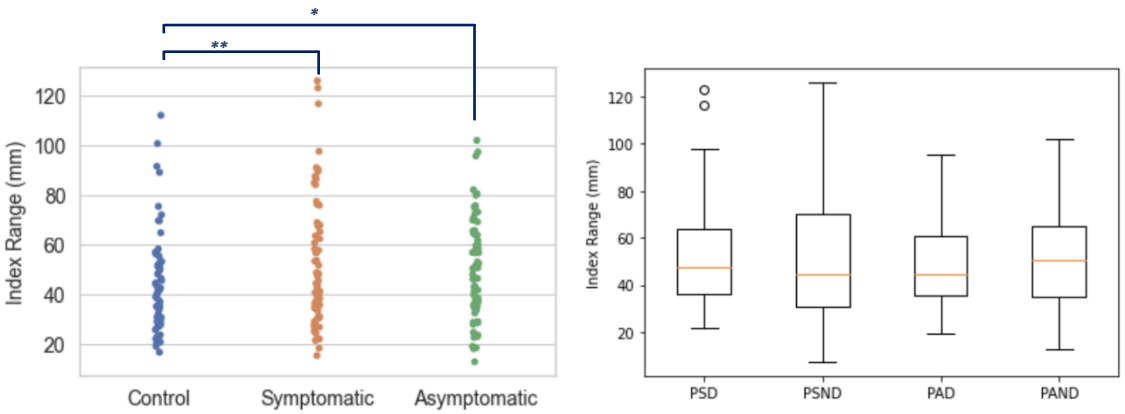
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	**0.017**
Control vs Patient Asymptomatic	**0.025**
Patient Symptomatic vs Patient Asymptomatic	0.878
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.717
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.922
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.608
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.804
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	0.947

Table 16. Results of the independent sample t-test. P-values for the Thumb Range parameter. *p<0.05, **p<0.005, ***p<0.0005.

- Index Range

The parameter 'Index Range' showed similar results to the previous variable, statistically significant differences between controls and symptomatic (p = 0.009) and non-symptomatic (p = 0.025) hands of the patients (see Table 17). In this case, statistically significant differences do appear between the symptomatic and asymptomatic hands (p= 0.025), which may indicate that the index finger is less affected than the thumb when performing this exercise. A greater dispersion of the values of the symptomatic hand of the patients can be observed (see Figure 71).



a) b)

Figure 71. Index Range a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

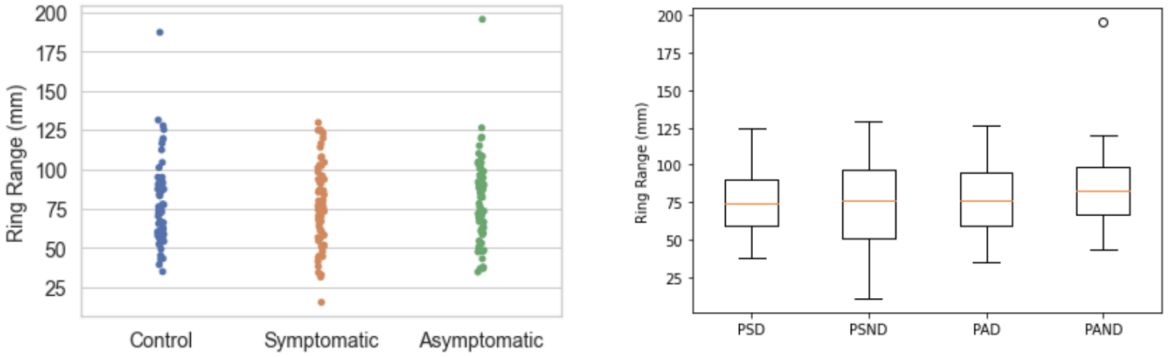
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	**0.009**
Control vs Patient Asymptomatic	**0.034**
Patient Symptomatic vs Patient Asymptomatic	0.618
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.824
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.493
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.750
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.709
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	0.959

Table 17. Results of the independent sample t-test. P-values for the Index Range parameter. *p<0.05, **p<0.005, ***p<0.0005.

- Ring Range

The parameter 'Ring Range' does not show any statistically significant differences (see Table 18). These results are closely related to the type of exercise being performed, since, like the middle finger, the ring finger does not move enough to detect any type of deficit in the separation of the fingers. This is also reflected in the distribution of values for each group (see Figure 72), with both the controls and the two sides of the patients moving in similar ranges.



a) b)

Figure 72. Ring Range a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

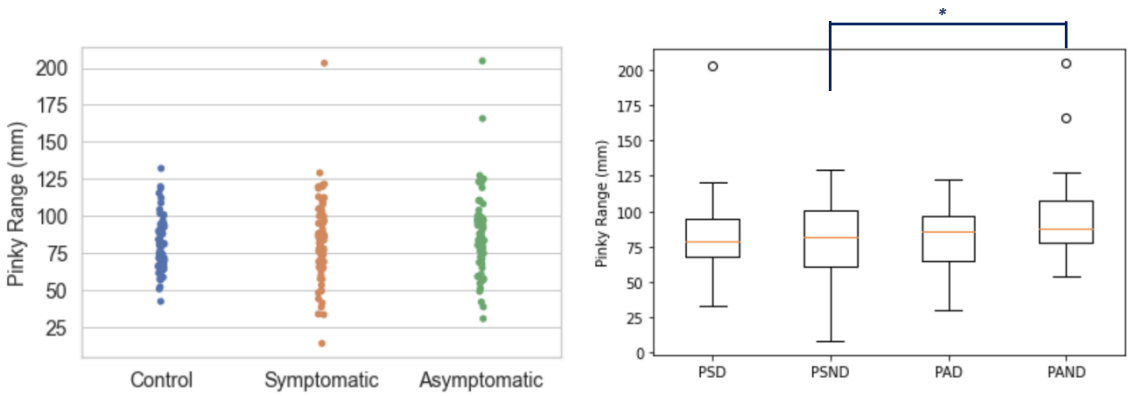
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	0.503
Control vs Patient Asymptomatic	0.529
Patient Symptomatic vs Patient Asymptomatic	0.302
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.928
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.986
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.168
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.924
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	0.235

Table 18. Results of the independent sample t-test. P-values for the Ring Range parameter. *p<0.05, **p<0.005, ***p<0.0005.

- Pinky Range

Pinky range does not show statistically significant differences between patients and controls (see Table 19). However, differences appear between the dominant and non-dominant sides of the controls (p = 2.9 e-10), being one of the few parameters in which this occurs, as commented in the previous section.



a) b)

Figure 73. Pinky Range a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

Results of the independent sample t-test

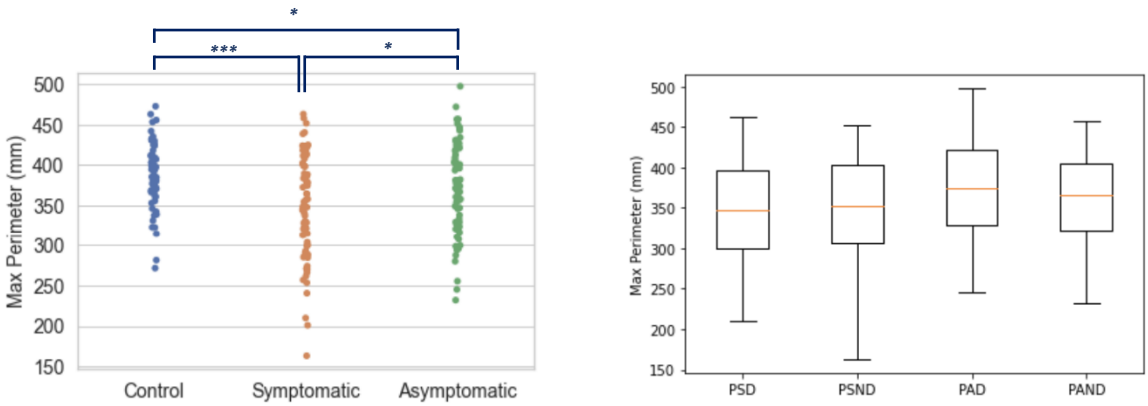
Variable	p-value
Control vs Patient Symptomatic	0.294
Control vs Patient Asymptomatic	0.358
Patient Symptomatic vs Patient Asymptomatic	0.167
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.481
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.581
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.101
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.812
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	**0.028**

Table 19. Results of the independent sample t-test. P-values for the Pinky Range parameter. *p<0.05, **p<0.005, ***p<0.0005.

- **Fist opening and closure exercise**

  - Maximum Perimeter

The maximum perimeter in the fist opening and closure, is also one of the most discriminatory. Statistically significant differences are found between controls and the symptomatic (p =6.95 e-7) and non-symptomatic (p = 0.040) side of the patients (see Table 20) indicating that the healthy side is not able to open the fist in the same way as the controls. In addition, differences between the symptomatic and theoretically healthy sides of the patients appear again (p = 0.032). These results are reflected in the distribution of the values (see Figure 74).



a) b)

Figure 74. Max Perimeter a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

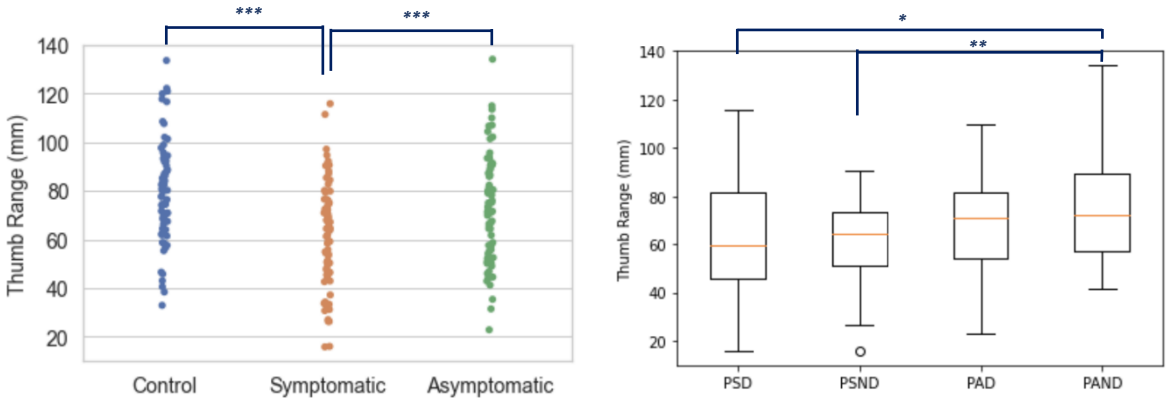
Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	**6.95 e-7**
Control vs Patient Asymptomatic	**0.040**
Patient Symptomatic vs Patient Asymptomatic	**0.032**
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.818
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.076
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	0.242
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.068
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	0.192

Table 20. Results of the independent sample t-test. P-values for the Max Perimeter parameter. *p<0.05, **p<0.005, ***p<0.0005.

- Thumb Range

The range of the thumb, in fist opening and closure, provides results quite similar to those of the previous parameter. Statistically significant differences appear between the control group and the symptomatic side of the patients (p = 2.17 e-6). However, in this case, the non-symptomatic side does not show any significant difference with the control group, suggesting that the difference that appeared with the maximum perimeter when opening the fist is not due to the thumb movement (see Table 21). This can be observed in Figure 75, where the distribution of values in the control group and the asymptomatic side are similar whereas the distribution followed by the symptomatic side shows lower values.



a) b)

Figure 75.Thumb Range a) Control and Patients b) Symptomatic and Asymptomatic hands by dominance.

Results of the independent sample t-test

Variable	p-value
Control vs Patient Symptomatic	**2.17 e-6**
Control vs Patient Asymptomatic	0.101
Patient Symptomatic vs Patient Asymptomatic	**0.005**
Patient Symptomatic Dominant vs Patient Symptomatic Non-Dominant	0.722
Patient Symptomatic Dominant vs Patient Asymptomatic Dominant	0.217
Patient Symptomatic Dominant vs Patient Asymptomatic Non-Dominant	**0.032**
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Dominant	0.083
Patient Symptomatic Non-Dominant vs Patient Asymptomatic Non-Dominant	**0.009**

Table 21. Results of the independent sample t-test. P-values for the Thumb Range parameter. *p<0.05, **p<0.005, ***p<0.0005.

CASE – CONTROL STRUDY SUMARY OF RESULTS

The tool is able to detect differences between controls and patients for all exercises. These differences appear even in patients with a FMA-UE score of 14 and NIHSS score of 0; so the tool is able to identify mild hand movement deficits that clinical scales are not able to quantify. In addition, some exercises are characterized by a greater capacity for discrimination: wrist flexo-extension and fist opening and closure, in particular and some parameters of the exercise 2.

These results show not only these movement deficits but also that patients perform some movements differently in order to achieve the goal, e.g. in exercise 2, they usually move the other fingers more in order to open and close the gripper. This finding can be relevant as it could be used as a novel indicator of the deficit in the clinical setting.

The tool was able to detect differences between controls and the asymptomatic side of the patient, indicating that the theoretically unaffected hand of the patients is actually involved. In fact there is a biological basis that may explain such involvement (through the ipsilateral motor pathway of the pyramidal tract explained in chapter 2 of this MSc thesis), or due to involvement of transhemispheral connecting fibers that may lead to a worse performance of the task when performing the exercises simultaneously with the symptomatic side. Either way this results in a poorer functionality that may affect the development of daily activities of stroke patients.

Although both dominant and non-dominant sides have been included in the statistical analyses, no common pattern has been found to conclude that there are differences depending on the dominance. These results are consistent with the analysis carried out for the controls.

Nonetheless, a higher impairment is appreciated on the non-dominant side of the patients (see Figure 65 to Figure 75), as they show lower values compared with the normality values obtained from the control group, but these results may be related to more severe strokes affecting the non-dominant cerebral hemisphere since, the patients with the non-dominant side affected presented lower scores on the scales.

5.1.5 Correlations between Kinematics and Clinical scales

To complete the study, correlations are performed between the kinematic data obtained for each parameter and the scores assigned in the clinical examination both with the NIHSS and FMA-UE scale.

Figure 86 shows the correlation matrix of the selected parameters and the scores of the clinical scales, with the Pearson's R values associated with each correlation.

There is a moderate correlation between the NIHSS score and the FMA-UE score (R = -0.56). This is due to the fact that the FMA-UE scale is much more specific for the upper limb and is able to distinguish deficits that the NIHSS cannot in relation to hand movement. Also, the correlation is negative since the NIHSS scores the deficit with higher values and FMA-UE with lower values.

Regarding correlations between the various kinematics variables themselves, high correlations between variables of the same exercise can be observed. Exercise 2 shows correlations with a Pearson's R of 0.68 for some variables, exercise 3 is the most significant since all fingers perform the same type of movement, obtaining a correlation with an R of 0.93 between the range of the little finger and the ring finger, and exercise 4 also shows these results with a correlation between the maximum perimeter and the range of the thumb with an R of 0.77. These findings support the robustness of the tool.

In addition to the correlation matrix, plots are elaborated to observe the behaviour of each kinematic variable against the clinical scale scores (see Figure 77 to Figure 87).

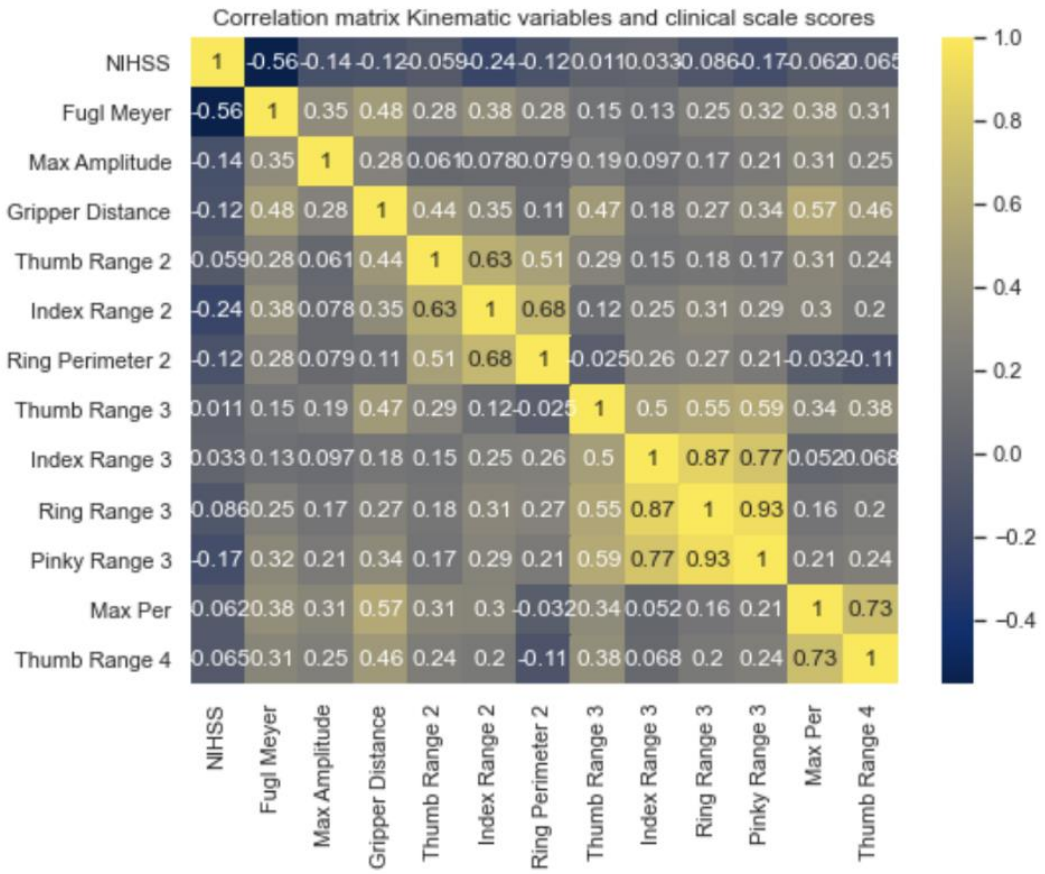


Figure 76. Correlation matrix Kinematic variables and clinical scale scores

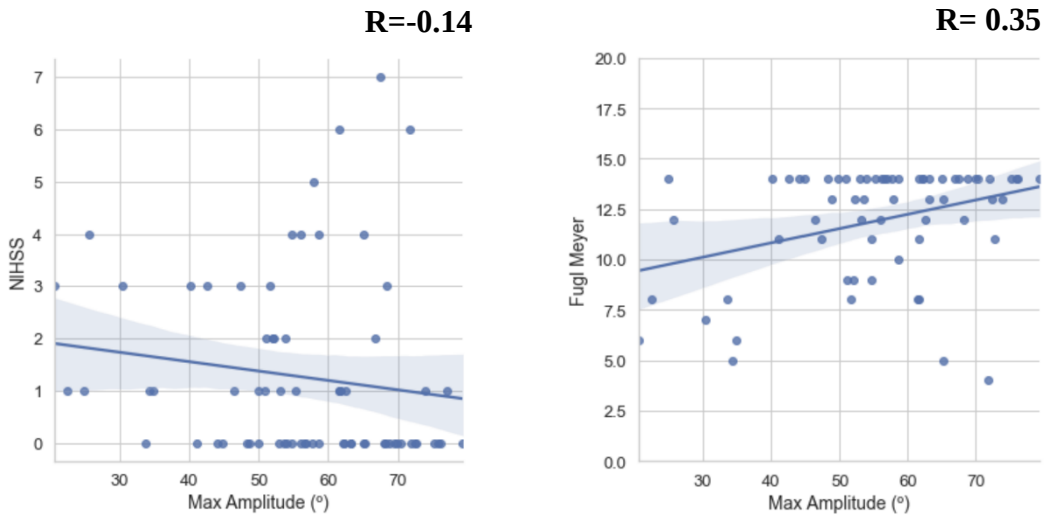
There is no correlation between the kinematic variables and the NIHSS score (maximum R value is -0.24 for the index range in exercise 2). This is because this scale is not specific enough to measure mild hand movement deficits.

Regarding the FMA-UE poor correlations can be perceived, although slightly better than those observed for the NIHSS scale, according to the fact that the FMA-UE is more discriminative. These findings are not surprising since most patients showed normal or nearly normal scores in the clinical while, abnormal kinematic data and suggest that the tool is measuring deficits not perceived by the clinical scales. This can be seen in the graphs in which there is a lot of variability of results in the kinematic variables between patients with the highest scores on the scales.

The parameter with the highest correlation with the FMA-UE scale is 'maximum gripper distance' with a Pearson's R of 0.48 (see Figure 78 b), patients with

lower scores on the scale getting a shorter gripper distance in exercise 2. A great dispersion of the kinematic data can be appreciated for patients with a score of 14 in the scale, taking values ranging from 65 mm to 140 mm. This can be appreciated to a greater or lesser extent in every parameter and could be explained by greater discriminative capacity and ability to quantify mild deficits of the tool in comparison with the clinical scales.

- **Wrist Flexo – Extension exercise**
  - Amplitude from the horizontal

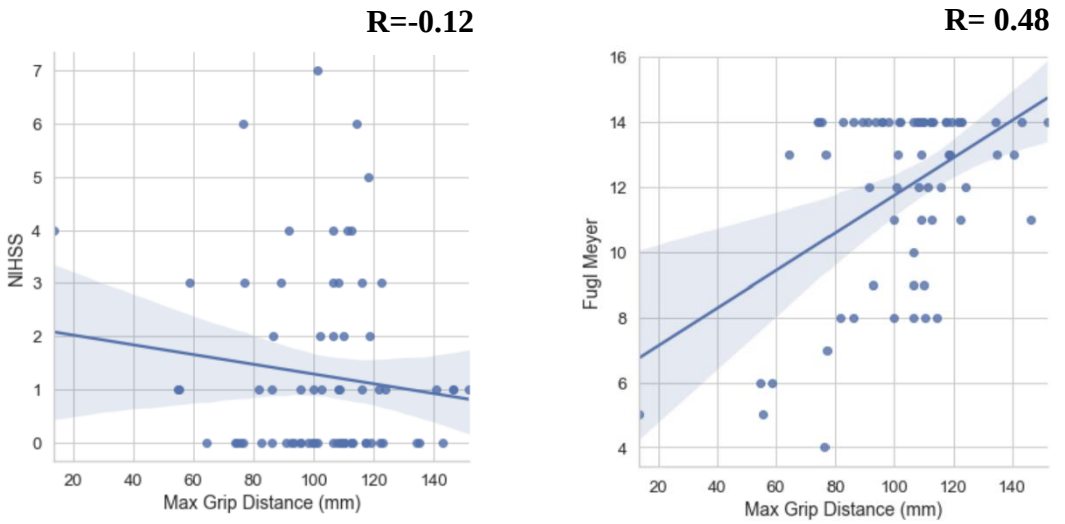


a) b)

Figure 77. Correlations between clinical scales and 'Amplitude from the Horizontal' parameter. a) NIHSS b) FMA - UE

- **Finger Grip exercise**

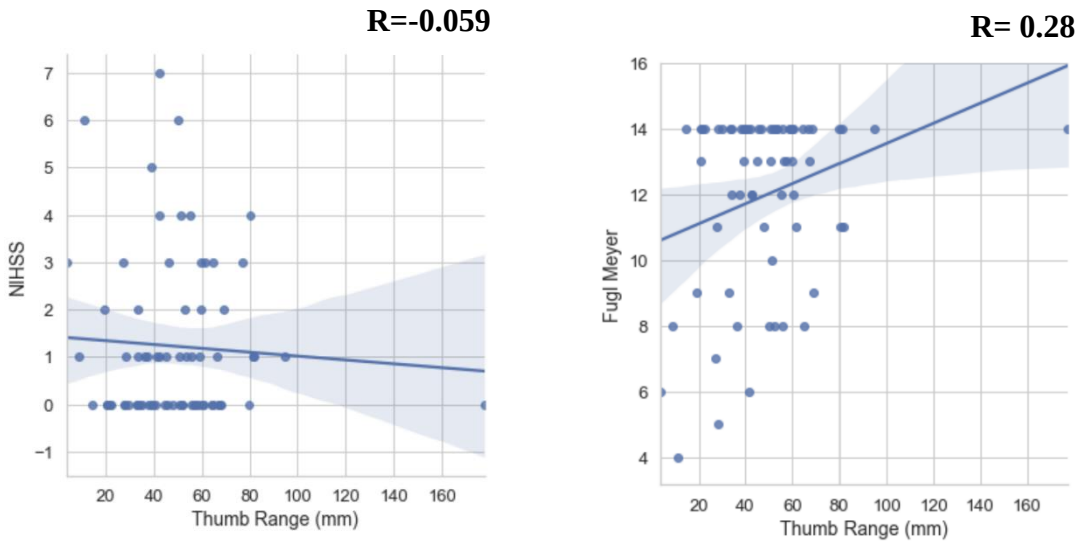
  - Maximum Grip Distance



a) b)

Figure 78. Correlations between clinical scales and 'Maximum Grip Distance' parameter. a) NIHSS b) FMA - UE

  - Thumb Range



a) b)

Figure 79. Correlations between clinical scales and 'Thumb Range' parameter. a) NIHSS b) FMA - UE

- Index Range

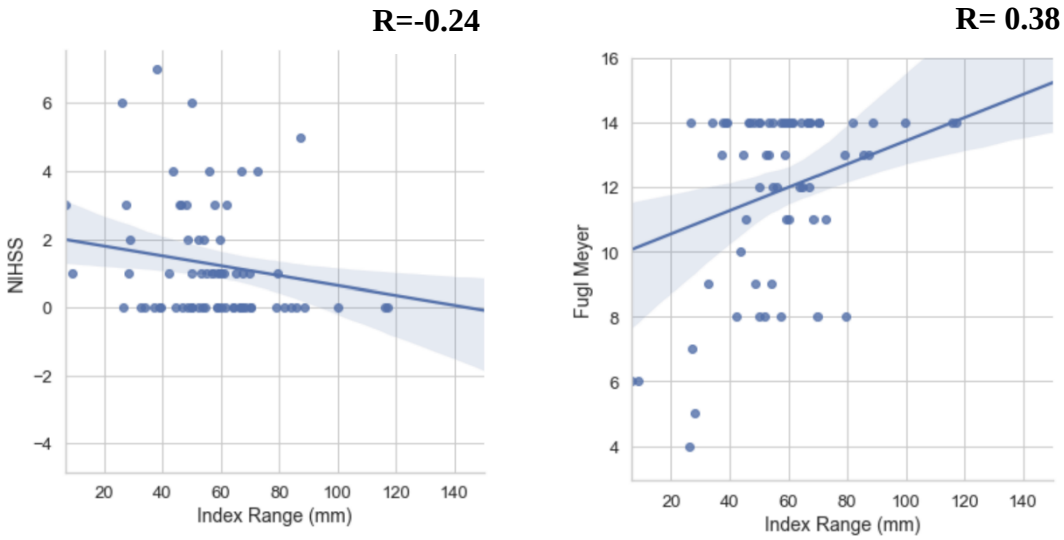


Figure 80. Correlations between clinical scales and 'Index Range' parameter. a) NIHSS b) FMA - UE

- Ring Perimeter

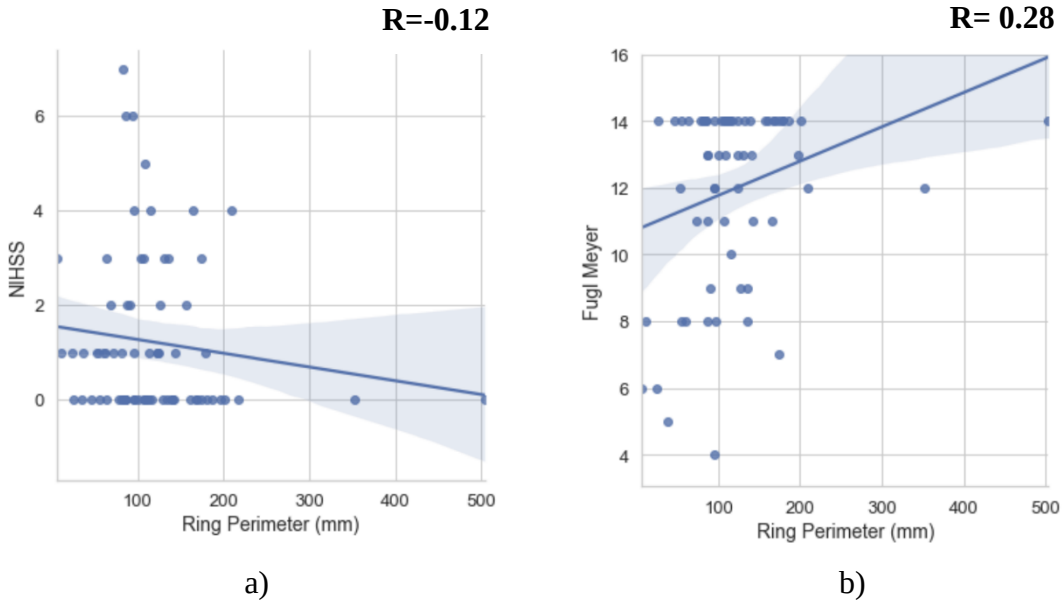
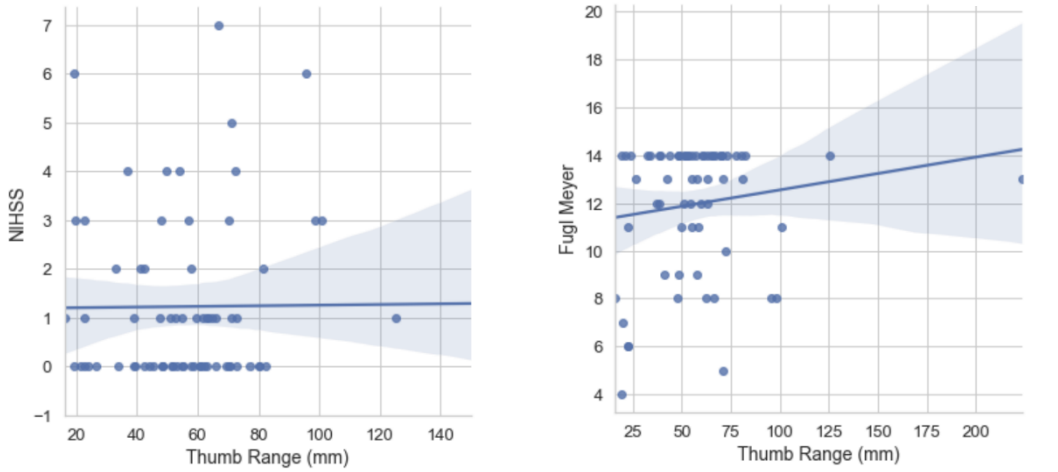


Figure 81. Correlations between clinical scales and 'Ring Perimeter' parameter. a) NIHSS b) FMA - UE

- **Finger Separation exercise**

  - Thumb Range

R= 0.011 **R= 0.15**

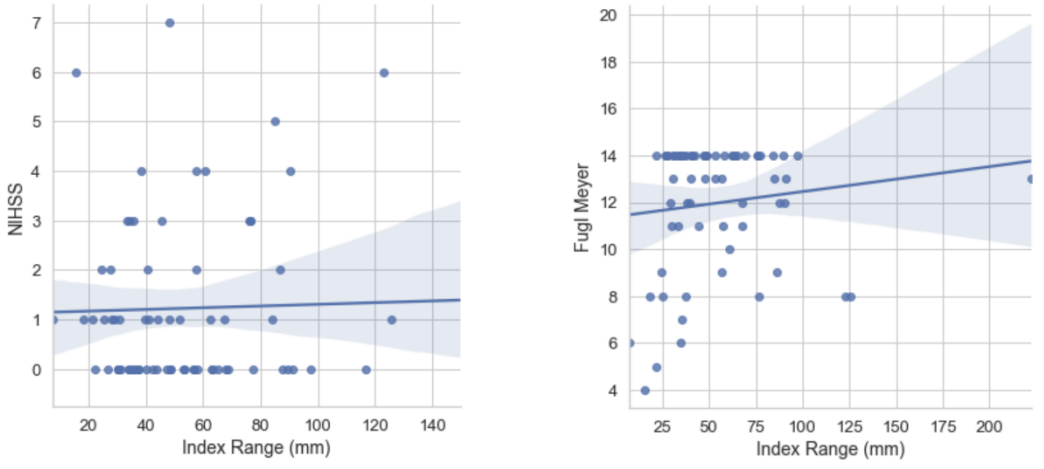


a) b)

Figure 82. Correlations between clinical scales and 'Thumb Range' parameter. a) NIHSS b) FMA - UE

  - Index Range

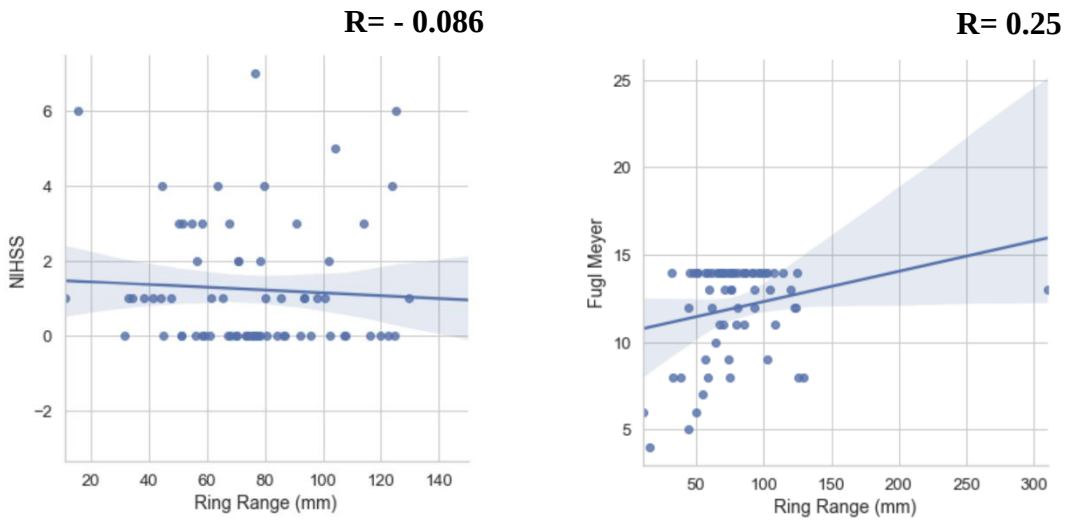
R= 0.033 **R= 0.13**



a) b)

Figure 83. Correlations between clinical scales and 'Index Range' parameter. a) NIHSS b) FMA - UE

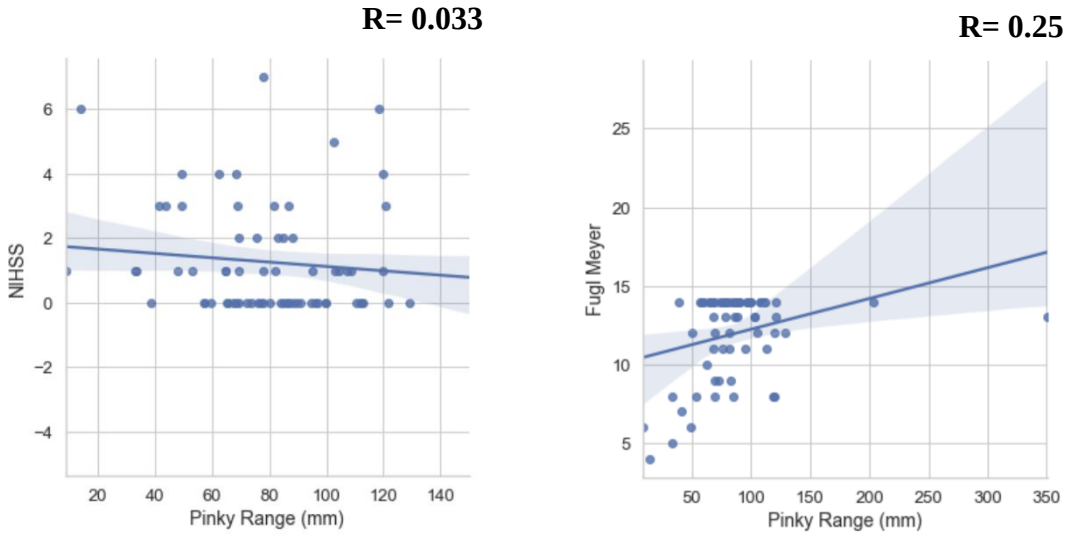
- Ring Range



a) b)

Figure 84. Correlations between clinical scales and 'Ring Range' parameter. a) NIHSS b) FMA - UE

- Pinky Range



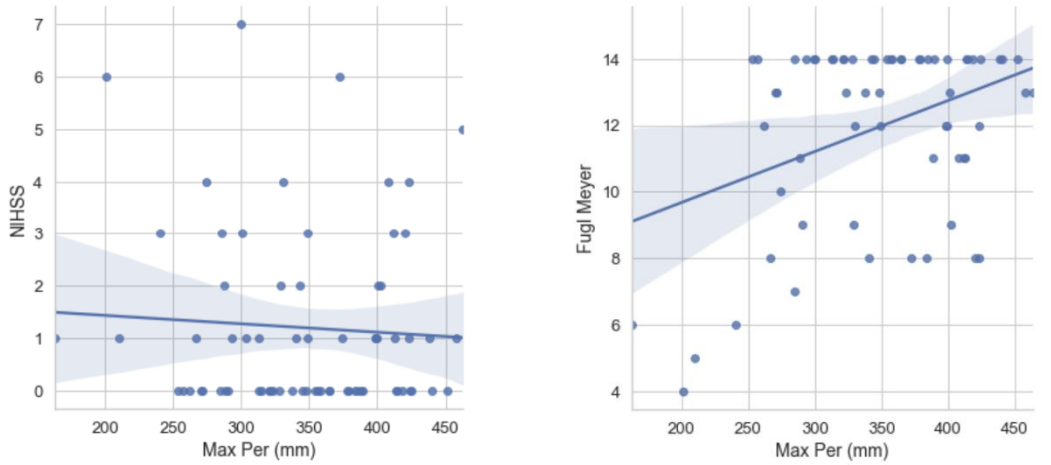
a) b)

Figure 85. Correlations between clinical scales and 'Pinky Range' parameter. a) NIHSS b) FMA - UE

- **Fist Opening and Closure exercise**

  - Max Perimeter

R= -0.062 **R= 0.38**

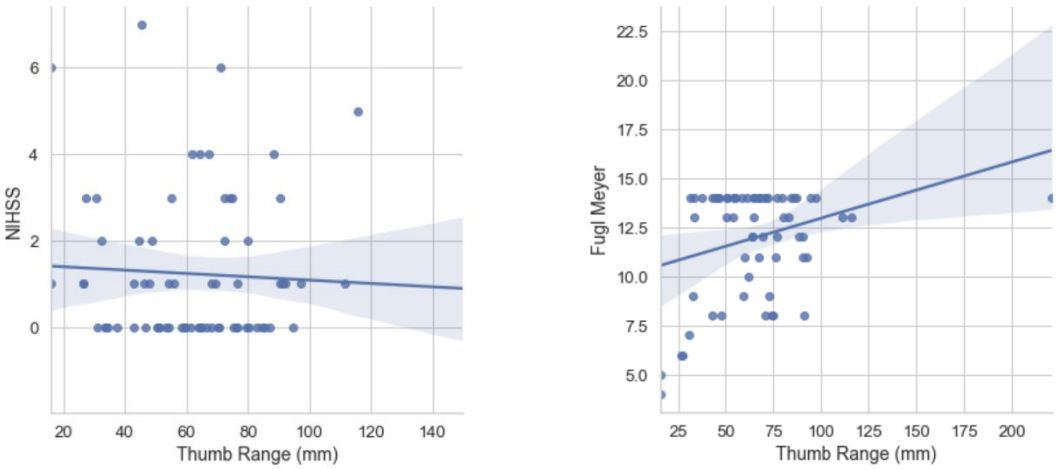


a) b)

Figure 86. Correlations between clinical scales and 'Max Perimeter' parameter. a) NIHSS b) FMA - UE

  - Thumb Range

R=-0.065 **R= 0.31**



a) b)

Figure 87. Correlations between clinical scales and 'Thumb Range' parameter. a) NIHSS b) FMA - UE

5.2 LONGITUDINAL STUDY

5.2.1 Clinical Data

Of the 79 patients recruited in the first part of the study 38 performed a second test in the follow-up study, being the mean time to follow up around six months. Characteristics including demographics, baseline and follow-up data and results of the Quality-of-Life survey are summarized in Table 22. The mean age remains almost the same as in the previous sample (64.23 ± 14.62 years), and a predominance of males can be appreciated again, 26 of them were men representing 68,42 % of the sample. Regarding the clinical assessment there were improvements in both NIHSS and FMA-UE scores.

Most of the cases included in the follow-up study presented territorial cerebral infarction representing 68,43% of the sample, and there were no TIA or patients with an undetermined diagnosis, since only patients recruited with a diagnosis of established stroke were selected for this longitudinal study.

The scores for the EuroQol5D survey were 0.81 ± 0.23 for the normalized value and 72.23 ± 19.89 for the analogue scale, these values represent a high variability in the self-reported quality of life. According to the evaluation criteria of the scale these values represent a mild to moderate impact on the quality of life of the subjects.

Variable	*Follow up Cases (n = 38)*
Age (years) (Mean +/- SD)	64.23 ± 14.62
Sex: Male, N (%)	26 (68,42 %)
Clinical Assessment (median /(Range))	
NIHSS score Baseline, median (range)	1, (0-7)
NIHSS score Follow up, median (range)	0, (0-2)
Fugl-Meyer-UE (hand ítems) score Baseline, median (range)	14, (4-14)
Fugl-Meyer-UE (hand ítems) score Follow up, median (range)	14, (12-14)
mRS, median (range)	0, (0 -3)
Stroke Subtype	
TIA, N (%)	----
Territorial cerebral infarction, N (%)	26 (68,43 %)
Lacunar cerebral infarction, N (%)	9 (23,68%)
Cerebral haemorrhage, N (%)	3 (7,89%)
Unknown, N (%)	----
Quality of Life (EuroQol5D)	
Normalized value (Mean +/- SD)	0.81 ± 0.23
Analogic Scale Value (Mean +/- SD)	72.23 ± 19.89
Follow Up	
Follow up period, days (Mean +/- SD)	201.96 ± 37.81

Table 22. Clinical Descriptive. Characteristics of the patients who completed the follow up process.

5.2.2 Analysis of kinematic data at Baseline and Follow-Up

For the longitudinal study comparisons between the kinematic data from hands of the patients at baseline and follow-up are made. Data from symptomatic and asymptomatic hands are compared, using the paired t-test explained in the methods.

The comparisons mentioned above are shown below, as well as the most representative results for each parameter.

The following abbreviations are used:

- BL: Baseline
- F-U: Follow-up

- **Wrist Flexo – Extension exercise**

A trend toward an increase in the maximum amplitude of exercise 1 is observed (see Figure 88) although the difference is not significant (see Table 23). This can be explained because there is not significant improvement in this exercise, but a lack of enough sensitivity cannot be ruled out.

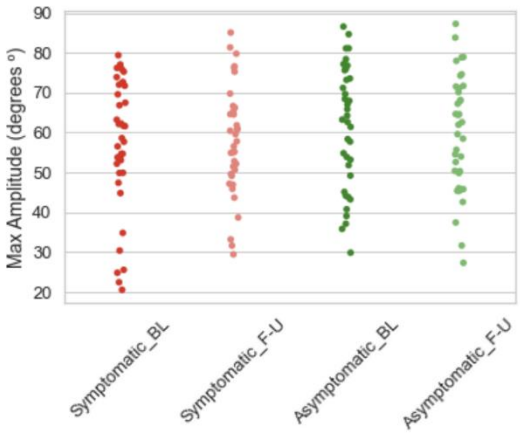


Figure 88. Exercise 1. Comparisons between Max Amplitude Baseline and Follow-up.

	Symptomatic BL v FU	Asymptomatic BL v FU
P-value	0.3301	0.8943

Table 23. Results from the paired t-test Exercise 1 (p-values). *p<0.05, **p<0.005, ***p<0.0005.

- **Finger Grip exercise**

Exercise 2 shows statistically significant differences in each selected variable (see Table 24). In particular, the parameter 'index range' shows evolutionary changes on both the symptomatic (p = 1.5 e-5) and asymptomatic (p = 5.9 e-5) sides. This can be observed in Figure 89 c) where values increased in the follow-up.

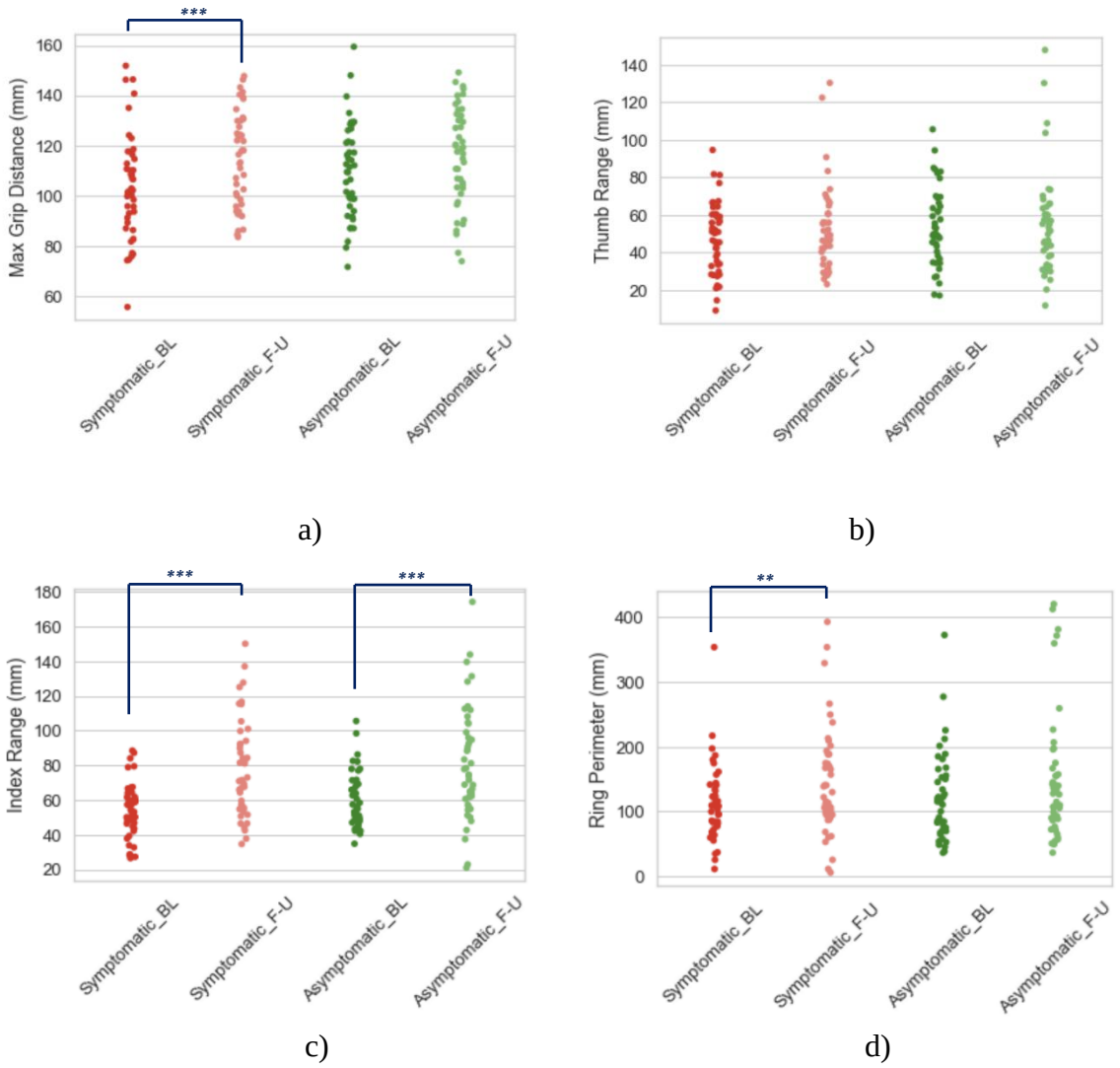


Figure 89. Exercise 2. Comparison of kinematic parameters between Baseline and Follow up a) Max grip distance Baseline and Follow-Up b) Thumb range Baseline and Follow-Up c) Index Range Baseline and Follow-Up d) Ring Perimeter Baseline and Follow-Up.

	Symptomatic BL v FU	Asymptomatic BL v FU
Max Gripper Distance	**0.0048**	0.1718
Thumb Range	0.1369	0.8746
Index Range	**1.5091 - 5**	**5.9857 - 5**
Ring Perimeter	**0.0441**	0.0647

Table 24. Results from the paired t-test Exercise 2 (p-values). *p<0.05, **p<0.005, ***p<0.0005.

- **Finger Separation exercise**

Exercise 3 does not show any statistically significant difference for any of the parameters studied (see Table 25). Therefore, no evolutionary changes associated with this exercise are detected. This can be seen in the distributions (see Figure 90), in which they have similar values in the acute phase and at follow-up.

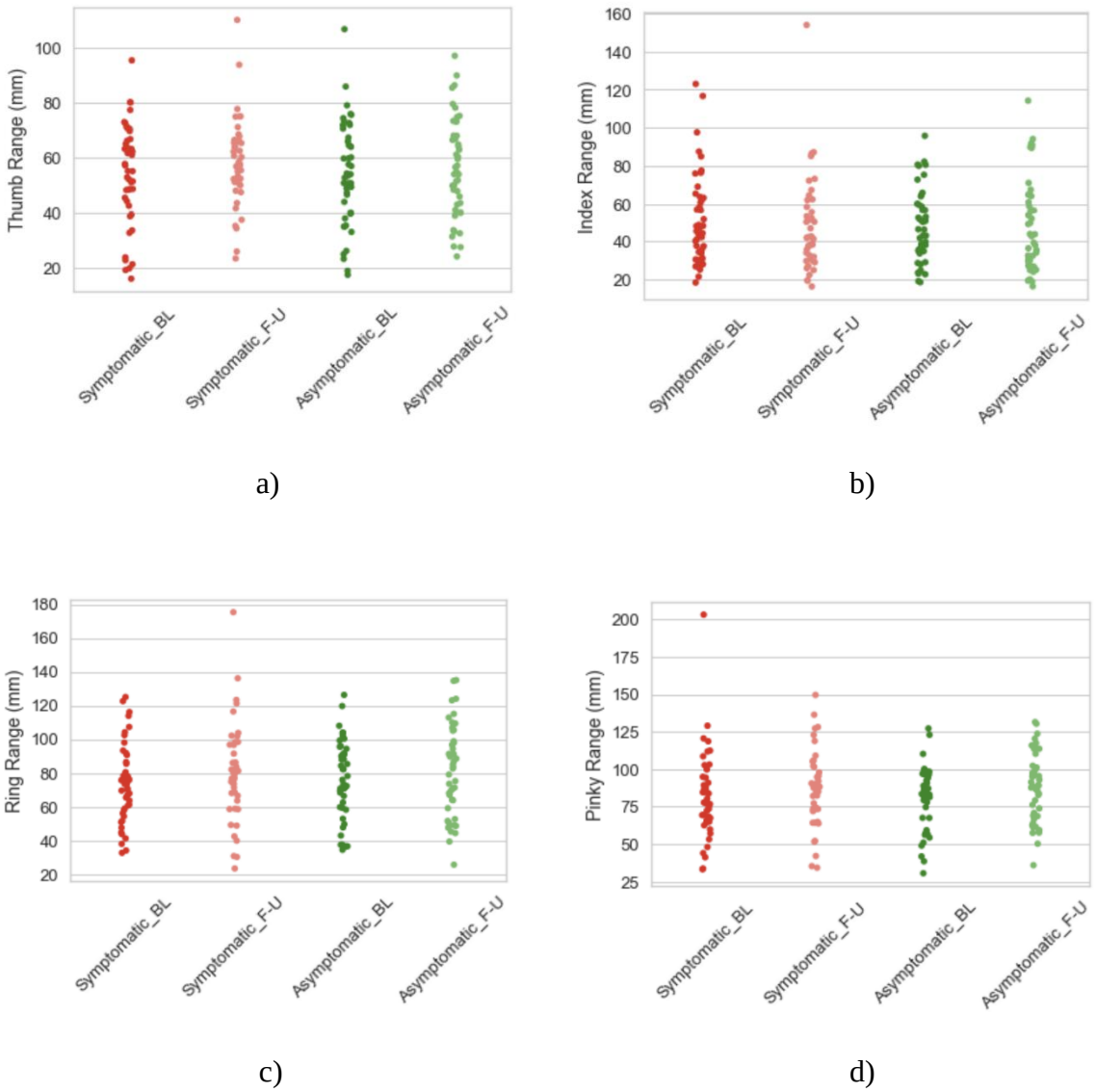


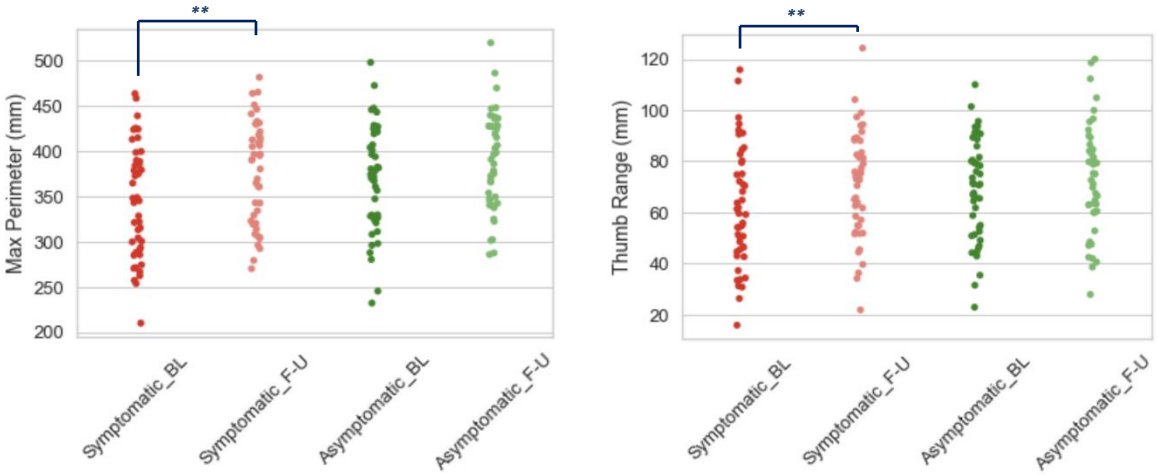
Figure 90. Exercise 3. Comparison of kinematic parameters between Baseline and Follow up a) Thumb range Baseline and Follow-Up b) Index range Baseline and Follow-Up c) Ring Range Baseline and Follow-Up d) Pinky range Baseline and Follow-Up.

	Symptomatic BL v FU	Asymptomatic BL v FU
Thumb Range	0.4922	0.7215
Index Range	0.2450	0.6875
Ring Range	0.3639	0.9274
Pinky Perimeter	0.3029	0.9437

Table 25. Results from the paired t-test Exercise 3 (p-values). *p<0.05, **p<0.005, ***p<0.0005.

- **Fist opening and closure exexrcise**

In the fist opening and closing exercise, statistically significant changes were detected in the two parameters studied (see Table 26). These changes appeared only in the symptomatic hand of the patients. Indicating that evolutionary changes are only detected in the affected hand, this is consistent with the state of the patients as the symptomatic hand has a greater possibility of improvement



a) b)

Figure 91.Exercise 4. Comparison of kinematic parameters between Baseline and Follow up a) Max Perimeter Baseline and Follow-Up b) Thumb range Baseline and Follow-Up.

	Symptomatic BL v FU	Asymptomatic BL v FU
Max Perimeter	**0.0180**	0.0697
Thumb Range	**0.0350**	0.8972

Table 26. Results from the paired t-test Exercise 4 (p-values). *p<0.05, **p<0.005, ***p<0.0005.

LONGITUDINAL STRUDY SUMARY OF RESULTS

The outcomes of the longitudinal study show that the tool is also able to detect evolutionary improvements in patients, although some exercises will be more discriminating when evaluating these changes. These are: finger grip and fist opening and closing. Specifically for exercise 2, the 'index range' parameter is the most discriminating parameter capable of distinguishing changes in evolution in both the asymptomatic and symptomatic hand with a high level of significance.

In general, the changes due to patient improvements are observed in the symptomatic hand (see Table 26), this makes sense as it is the side with the most potential for improvement between the initial study and follow-up.

In addition, for the exercises where there are no statistically significant differences (Exercise 1 and 3), small trends of change between baseline and follow-up are still discernible in the graphs although they are not large enough to be significant. This can be explained by the fact that the changes are not significant enough and may not be indicating a lack of sensitivity of the tool when measuring the movement of these exercises.

5.2.3 Correlations between Kinematics and Quality of Life

Patients answered a quality-of-life survey at follow-up and correlations between kinematic data and the results of the survey were carried out, in order to describe any relationship between motor performance according to the kinematic and a better quality of life.

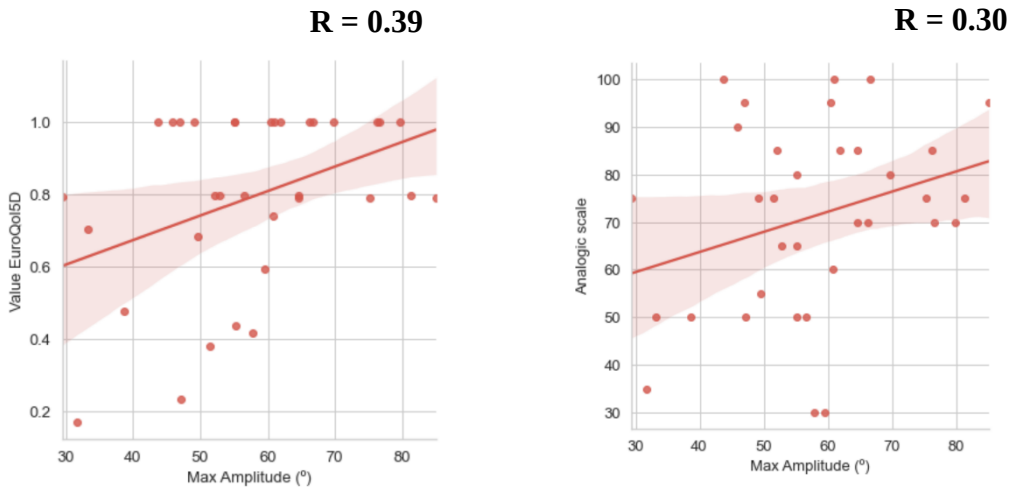
In addition, in order to better understand these results, an specific study is carried out in which each of the variables is correlated with the quality-of-life score. Results are showed below (see Figure 92 to Figure 102).

The scores in the quality-of-life scales are not particularly correlated with the kinematic variables. Only a poor correlation was found between thumb range in exercise 2 (see Figure 94 a) and the objective value of the Euroqol5D scale (Pearson's R = 0.42). These results are associated with the great dispersion of results, since for the same value of the quality-of-life scale there is a wide range in the values of the kinematic variables, e.g. see Figure 95 a).

These poor correlations may be due to the fact that the quality of life scale is not discriminative enough with mild impairments (problem that also appeared with the rest of clinical scales to assess upper limb movement), as the questions of the survey are focused on general aspects of activities of daily living and not centred exclusively on the upper limb impairment. Also, results vary greatly due to the subjectivity of each individual when answering the survey and to the possibility that other conditions apart from the motor deficit may influence the response.

- **Wrist Flexo – Extension exercise**

  - Amplitude from the horizontal



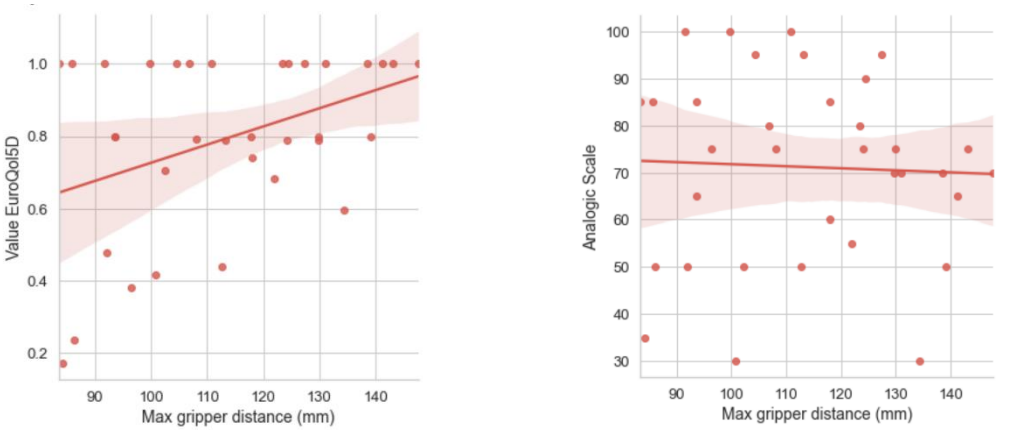
a) b)

Figure 92. Exercise 1. 'Amplitude from the Horizontal' parameter. Correlation between Kinematics and Quality of Life.

- **Finger Grip exercise**

  - Max gripper amplitude

R = 0.39 **R = -0.04**

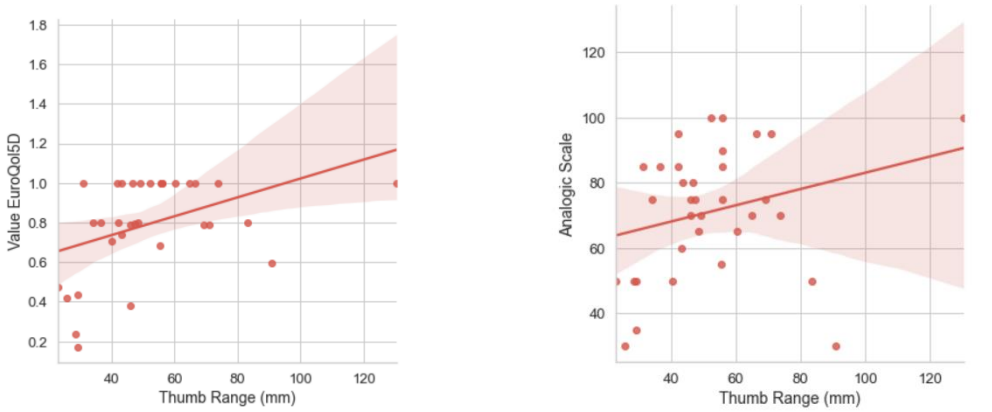


a) b)

Figure 93. Exercise 2.'Max gripper amplitude' parameter. Correlation between Kinematics and Quality of Life.

  - Thumb Range

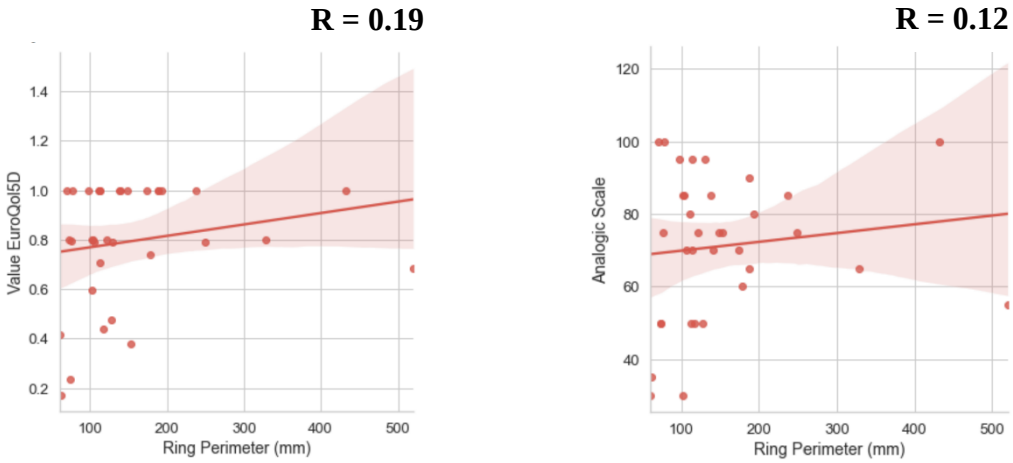
R = 0.42 **R = 0.27**



a) b)

Figure 94.Exercise 2.'Thumb Range' parameter. Correlation between Kinematics and Quality of Life.

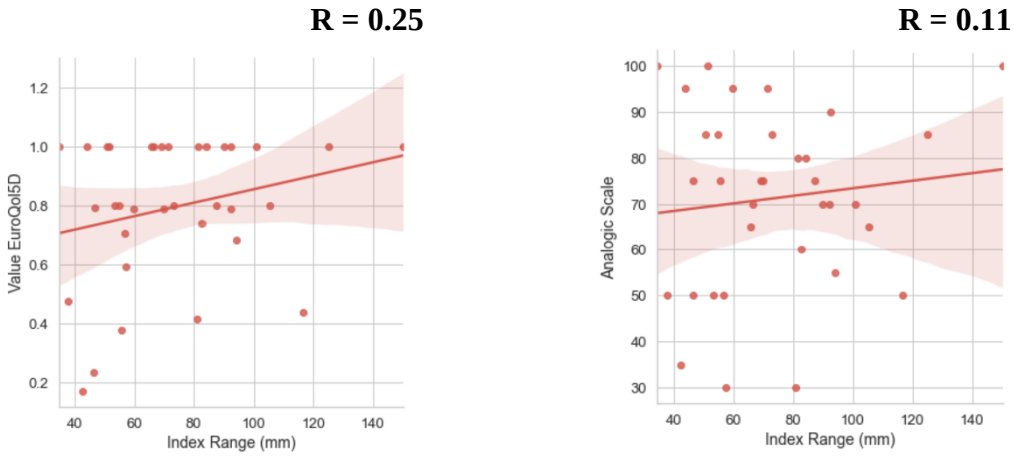
- Index Range



a) b)

Figure 96. Exercise 2. 'Ring Perimeter' parameter. Correlation between Kinematics and Quality of Life.

- Ring Perimeter

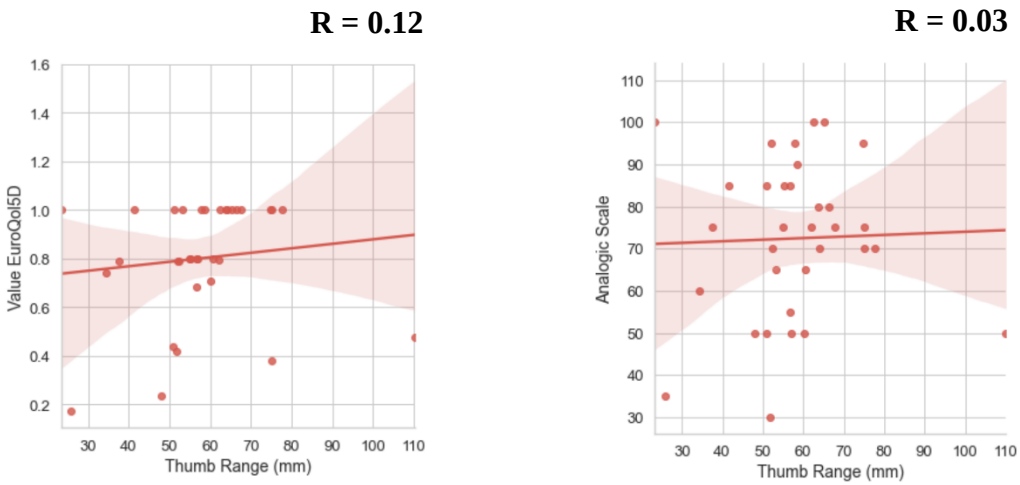


a) b)

Figure 95. Exercise 2. 'Index Range' parameter. Correlation between Kinematics and Quality of Life.

- **Finger Separation exercise**

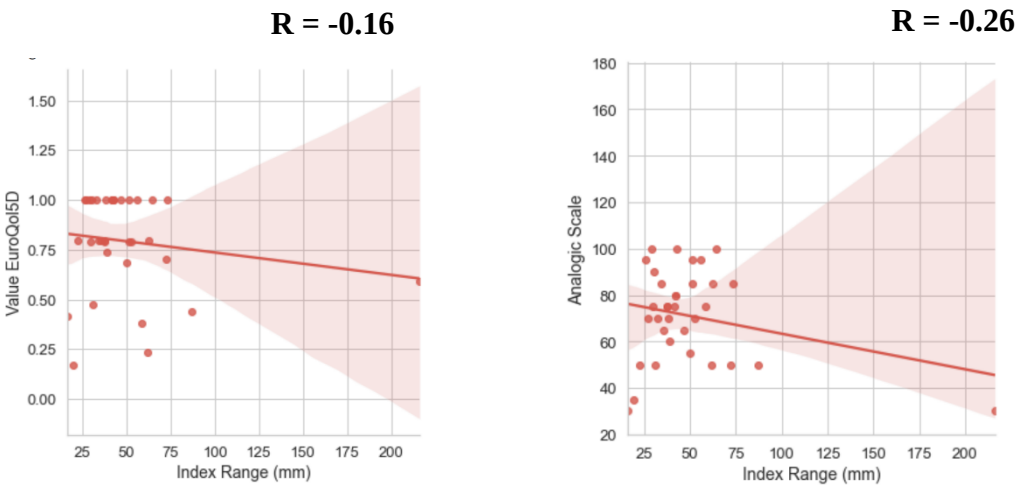
  - Thumb Range



a) b)

Figure 97. Exercise 3. 'Thumb Range' parameter. Correlation between Kinematics and Quality of Life.

  - Index Range

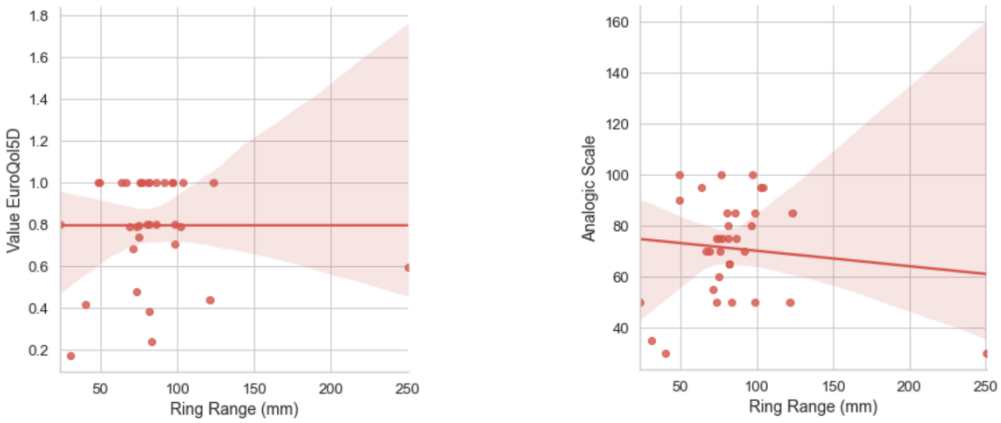


a) b)

Figure 98. Exercise 3. 'Index Range' parameter. Correlation between Kinematics and Quality of Life.

- Ring Range

R = 0.001 **R = -0.11**

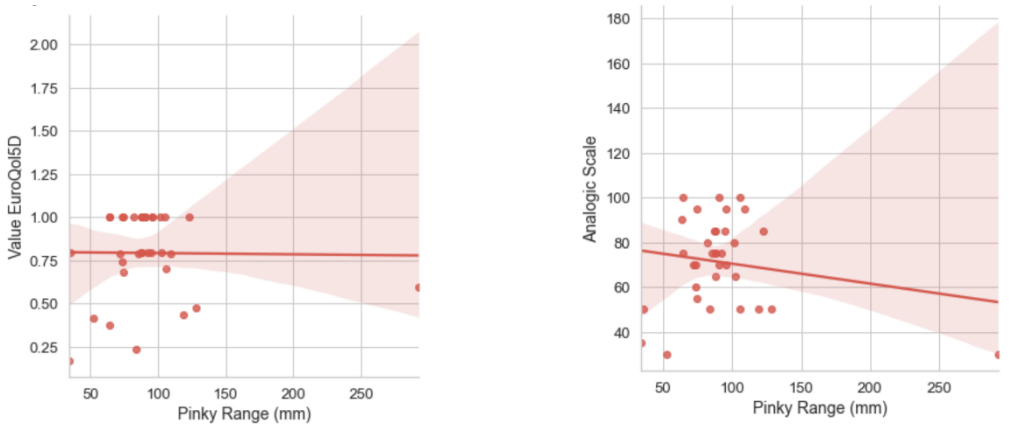


a) b)

Figure 99. Exercise 3. 'Ring Range' parameter. Correlation between Kinematics and Quality of Life.

- Pinky Range

R= -0.012 **R = -0.19**



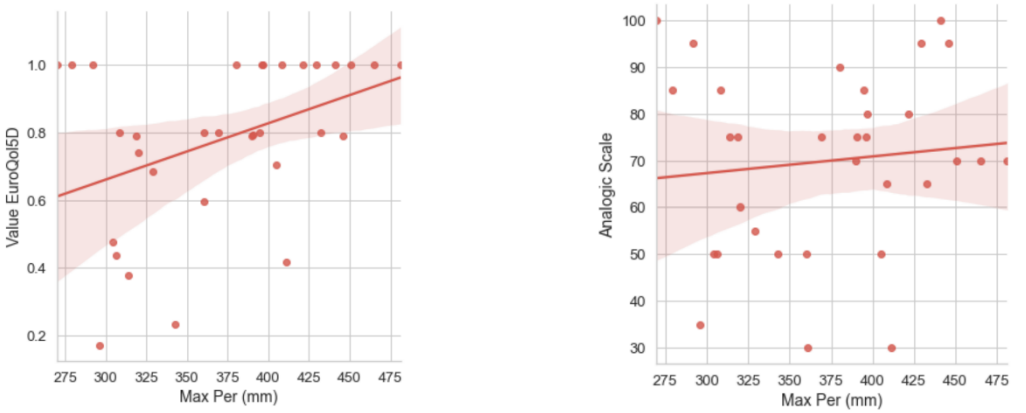
a) b)

Figure 100.Exercise 3. 'Pinky Range' parameter. Correlation between Kinematics and Quality of Life.

- **Fist Opening and closure exercise**

  - Max Perimeter

R = 0.40 **R = 0.11**

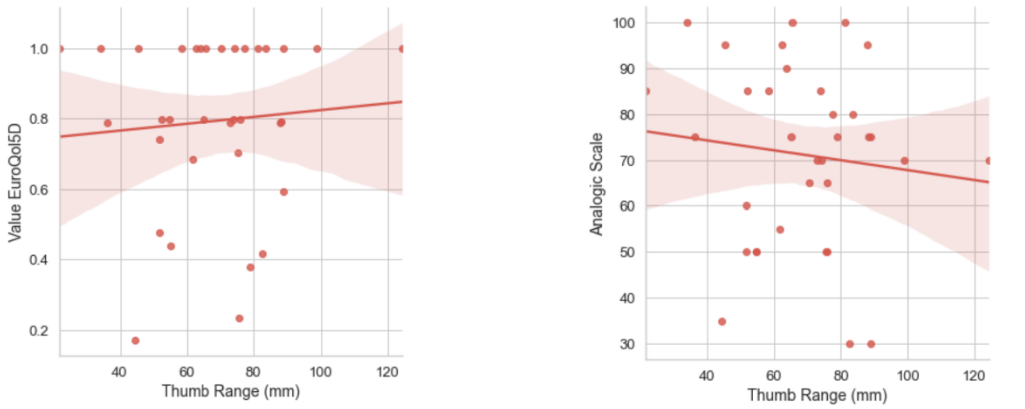


a) b)

Figure 101. Exercise 4.'Max Perimeter' parameter. Correlation between Kinematics and Quality of Life.

  - Thumb Range

R = 0.08 **R = 0.11**



a) b)

Figure 102. Exercise 4. 'Thumb Range' parameter. Correlation between Kinematics and Quality of Life.

5.3 DISCUSSION OF THE RESULTS

The results obtained respond to the principal objective of this thesis, the validation of an optical motion capture tool capable of distinguishing mild hand movement deficits in patients who have suffered from a stroke.

The outcomes of the case-control study confirm the feasibility of the tool to distinguish between healthy subjects and patients with mild upper limb deficits in each of the exercises. The variables with the highest discrimination capacity are: maximum amplitude from the horizontal for exercise 1; maximum gripper distance, index finger range and ring finger perimeter for exercise 2; thumb range, index finger range and little finger range for exercise 3 and maximum perimeter and thumb range for exercise 4. The rest of the variables show hardly any significant results and could therefore be discarded when determining whether a patient has a deficit or not. This is because the areas associated with these variables may be less affected by the stroke or because the tool itself is not able to detect changes in these variables in particular.

The analysis of the correlations between the clinical scale scores and the kinematic variables could explain the originally stated hypothesis that these scales are not sufficiently discriminatory for detecting mild hand movement deficits. The kinematic analysis tool can detect small differences in the execution of a movement, which makes it possible to grade the deficit much more precisely than scales, which actually categorize the deficit and therefore discriminate worse.

Differences were found between controls and patients even among those with the highest scores that are classified by the scales as without deficit. This is illustrated with a high variability in the values of the kinematic parameters, i.e. for a score of 14 on the FMA scale a wide range of values appears for the different kinematic variables.

As a consequence of the results obtained in the analysis, interesting behaviour patterns emerge that had not been considered at the outset:

- The theoretically healthy side of the patients, which in all cases had a maximum score on the clinical scales (indicating that they did not show any deficits), demonstrated statistically significant

differences with the controls and in some cases with the respective symptomatic side. This indicates that the healthy side is actually affected but in a different way than the symptomatic side, which is closely related to what was explained in Chapter 2 of this thesis with the existence of the anterior corticospinal tract uncrossed (see Figure 5). The alternative reason for this is that by performing the exercises simultaneously with the symptomatic side of the patient, the theoretically healthy side of the patient may not be able to perform the exercise effectively. In either case this translates into a deficit on the side ipsilateral to the lesion that can affect patients' ability to carry out daily activities.

- Differences are found when performing certain exercises that aimed to compensate deficits associated with the stroke. This can be clearly appreciated in the study of the parameter 'ring perimeter' in exercise 2, which, as the deficit increases, the finger movement increases in order to successfully perform the gripper exercise.

- These findings that become evident thanks to this tool, could be considered as surrogate indicators of the deficit and arise as novel signs that could be applied to quantify the deficit in clinical practice,

The results of the longitudinal study demonstrated the capability of the tool to discriminate the evolutionary deficit of the patients. However, these differences were not as evident as those between cases and controls and were only shown in the parameters of exercises 2 and 4. This may indicate that, in this particular study, evolutionary changes only occurred in these two exercises or that the parameters associated with wrist flexion-extension and finger separation are not sufficiently discriminative to detect minimal changes in evolution.

Regarding the correlation with the quality-of-life scores, no highly significant values were found due to the high variability of results for the quality of life, especially for the variable associated with the visual analogue scale.

A different approximation could be to correlate the difference associated with the evolution over time between the different examinations, instead of correlating with the final value of the kinematic parameter. In such a way that the quantification of the improvement is correlated with the value of the quality-of-life scale at that time. However, it seems clear that these quality of life scales are not sufficiently discriminative to take into account mild upper limb impairments.

6 DISCUSSION

6.1 Conclusions

With the development of this MSc thesis, the main objectives set out at the beginning of the thesis have been achieved, which include obtaining a vision of the stroke disease, the deficits it causes and their impact on the functionality and on activities of daily living of patients who suffer from it. Also, a global vision of stroke management and an understanding of the troubles that physicians have to face when evaluating such deficits have been achieved as well as the understanding the different scales used. Finally, the validation of the proposed computational tool to objectify the movement of the hands through optical technology has been made.

In addition, the following conclusions have been reached:

- The software proposed for kinematic analysis using optical technology provides a useful tool to objectify hand functional deficits after a stroke. Symptomatic patients showed statistically significant differences with healthy controls in various kinematic parameters measured with this tool.

- The tool is able to identify mild hand motor deficits that the conventional clinical scales are not able to discriminate. Patients with no deficit when assessed by clinical scales do have in fact poorer performance than controls when evaluated by the tool.

- The longitudinal study has demonstrated the ability of the tool to detect evolutionary changes in hand movement in patients who have suffered a stroke.

- Advances in the development of optical motion capture technologies and new tracking algorithms have made it possible to obtain an accuracy adequate to measure movements that require high precision, without complex tools or devices that are too cumbersome, expensive or difficult to use. Specifically, the development of this tool may aid in the

accurate assessment of disability and in optimization of rehabilitation therapies.

- Since this was a pilot study, the lack of significant data in some of the variables studied may be related to the small sample size and the large variability observed in the patient data.In any case, the results suggest that this is a promising tool with great applicability in practice.

- Results obtained from the validation study are very promising, as they not only validate the tool as an objective hand movement measurement tool for clinical use, but also revealed patient movement behaviours that have not been previously described in the literature.

In conclusion, the validation of an objective measurement system for hand movement in stroke patients has been successfully carried out, which is expected to have a great utility in the clinical environment both in the diagnostic process and in the rehabilitation stage of the patients who have suffered from a stroke.

6.2 Future Lines

The fact that this thesis has been successfully completed provides a wide range of possibilities to be further exploited:

Further data collection is proposed to achieve a much more robust database that eliminates the problems caused by the small sample size, such as the age difference between groups. As a consequence of this, a migration to a consistent database where both clinical and kinematic data are unified can be considered.

Introduce artificial intelligence and automatic classification algorithms since there is a large enough sample to start exploring this aspect and determine if these algorithms are able to distinguish mild hand movement deficits more accurately than clinical scales.

Improve the graphical interface of the application by adding, for example, a summary screen where the clinician can quickly see the patient's status once the exercises have been completed. Additionally, consider the introduction of new exercise

screens with different environments that continue to measure the key parameters of the hand, but also adding a rehabilitative approach of the movement.

To explore the behavior of the theoretically healthy limb. For this purpose it is proposed to perform the exercises with the hands apart and analyze what happens in each exercise. In this way it will be possible to identify if the theoretically healthy side is really affected without the influence of the symptomatic side when performing the test.

Adaptation of the software to assess different batteries of exercises designed to explore specific functionalities is also possible which may extend the applicability of the tool.

Finally, there is also the possibility of entering the market with this tool, since it is something innovative that solves a problem present in a large part of the population and can be affordable for the majority of users.

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APPENDIX A

The Code for the EuroQol 5D calculator interface is as follows:

```
import numpy as np
from tkinter import *
from PIL import ImageTk, Image
import os
window = Tk()
window.title('Calidad de vida')

label = Label(window,text="\n Escala EuroQol 5D", font = ('Arial Bold', 15))
label.pack()

window.geometry('700x750')


var1 = StringVar()
var2 = StringVar()
var3 = StringVar()
var4 = StringVar()
var5 = StringVar()

var1.set(0)
var2.set(0)
var3.set(0)
var4.set(0)
var5.set(0)

label_movilidad = Label(window, text = '\nMOVILIDAD', font = ('Arial', 10))
label_movilidad.pack(anchor = 'w')

rad1_movilidad = Radiobutton(window,text='  No tengo problemas para caminar',variable = var1, value=1)
rad2_movilidad = Radiobutton(window,text='  Tengo algunos problemas para caminar',variable = var1, value=2)
rad3_movilidad = Radiobutton(window,text='  Tengo que estar en la cama',variable = var1, value=3)

rad1_movilidad.pack(anchor = 'w')
rad2_movilidad.pack(anchor = 'w')
rad3_movilidad.pack(anchor = 'w')

label_movilidad = Label(window, text = '\nCUIDADO PERSONAL', font = ('Arial', 10))
label_movilidad.pack(anchor = 'w')

rad1_cuidado = Radiobutton(window,text='  No tengo problemas para realizar las actividades de cuidado personal',variable = var2, value=1)
rad2_cuidado = Radiobutton(window,text='  Tengo algunos problemas para realizar las actividades de cuidado personal',variable = var2, value=2)
rad3_cuidado = Radiobutton(window,text='  Tengo que estar en la cama',variable = var2, value=3)

rad1_cuidado.pack(anchor = 'w')
rad2_cuidado.pack(anchor = 'w')
rad3_cuidado.pack(anchor = 'w')

label_movilidad = Label(window, text = '\nACTIVIDADES COTIDIANAS', font = ('Arial', 10))
label_movilidad.pack(anchor = 'w')

rad1_cuidado = Radiobutton(window,text='  No tengo problemas para realizar mis actividades cotidianas',variable = var3, value=1)
rad2_cuidado = Radiobutton(window,text='  Tengo algunos problemas para realizar mis actividades cotidianas',variable = var3, value=2)
rad3_cuidado = Radiobutton(window,text='  Soy incapaz de ralizar mis actividades cotidianas',variable = var3, value=3)

rad1_cuidado.pack(anchor = 'w')
rad2_cuidado.pack(anchor = 'w')
rad3_cuidado.pack(anchor = 'w')

label_movilidad = Label(window, text = '\nDOLOR Y MALESTAR', font = ('Arial', 10))
label_movilidad.pack(anchor = 'w')

rad1_cuidado = Radiobutton(window,text='  No tengo dolor ni malestar',variable = var4, value=1)
rad2_cuidado = Radiobutton(window,text='  Tengo dolor moderado o malestar',variable = var4, value=2)
rad3_cuidado = Radiobutton(window,text='  Tengo mucho dolor o malestar',variable = var4, value=3)

rad1_cuidado.pack(anchor = 'w')
rad2_cuidado.pack(anchor = 'w')
rad3_cuidado.pack(anchor = 'w')

label_movilidad = Label(window, text = '\nANSIEDAD Y DEPRESIÓN', font = ('Arial', 10))
label_movilidad.pack(anchor = 'w')

rad1_cuidado = Radiobutton(window,text='  No estoy ansioso ni deprimido',variable = var5, value=1)
rad2_cuidado = Radiobutton(window,text='  Estoy moderadamente ansioso o deprimido',variable = var5, value=2)
rad3_cuidado = Radiobutton(window,text='  Estoy muy ansioso o deprimido',variable = var5, value=3)
```

```
rad1_cuidado.pack(anchor = 'w')
rad2_cuidado.pack(anchor = 'w')
rad3_cuidado.pack(anchor = 'w')

Constante = 0.1502
Movilidad = 0.0897
Cuidado_Personal = 0.1012
Actividades_Cotidianas = 0.0551
Dolor_Malestar = 0.0596
Ansiedad_Depresion = 0.0512
N3 = 0.2119
parametros = [Constante,Movilidad,Cuidado_Personal,Actividades_Cotidianas,Dolor_Malestar,Ansiedad_Depresion,N3]
valores = np.zeros(5)


def clicked():

    valores[0] = var1.get()
    valores[1] = var2.get()
    valores[2] = var3.get()
    valores[3] = var4.get()
    valores[4] = var5.get()

    resultado = 1
    a = 0

    for i in range(len(valores)):
        if valores[i] == 1:
            resultado = resultado
        if valores[i] != 1:
            resultado = 1 - Constante
    for i in range(len(valores)):
        if valores[i] == 2:
            resultado = resultado - parametros[i+1]
    for i in range(len(valores)):
        if valores[i] == 3:
            a = 1
            resultado = resultado - 2*  parametros[i+1]
    if a == 1:
        resultado = resultado - N3
    resultado = round(resultado,4)

    label_resultado = Label(window, text = '\nEl resultado es %s' %resultado, font = ('Arial', 12))
    label_resultado.place(x = 270,y = 650)

Aceptar = Button(window, text = 'Aceptar', command = clicked)
Aceptar.pack(anchor = 'center')

img  = Image.open("Escala.png")
photo=ImageTk.PhotoImage(img)
lab=Label(image=photo).place(x=500,y=70)

window.mainloop()
```

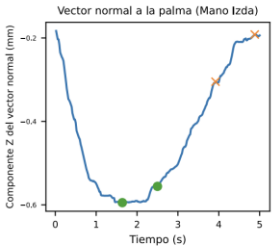
APPENDIX B

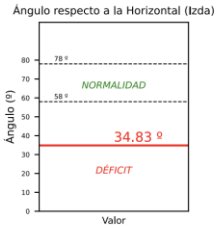
An example of a report of results for a patient with stroke is showed below:

Ejercicio 1: Flexo - Extensión de muñeca

Mano Izquierda

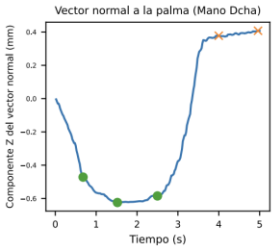
Ángulo máximo desde la horizontal Izda : 34.83 º

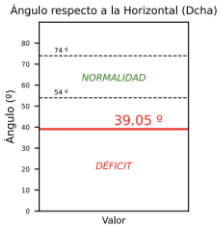




Mano Derecha

Ángulo máximo desde la horizontal Dcha : 39.05 º

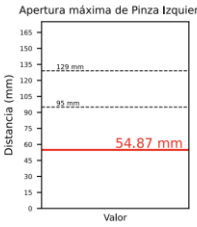


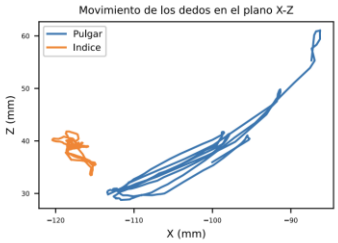


Ejercicio 2: Pinza Índice - Pulgar

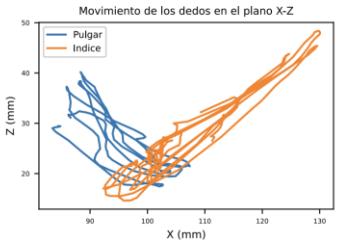
2.1 Apertura máxima de Pinza 'mm'

Mano Izquierda





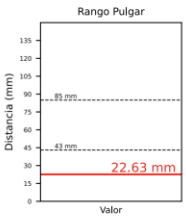
Mano Derecha

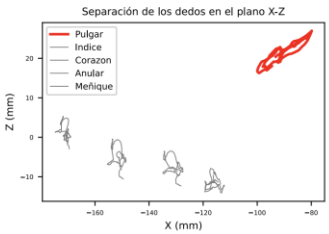


Ejercicio 3: Separación de dedos

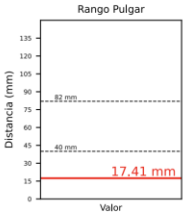
3.1 Rango Pulgar 'mm'

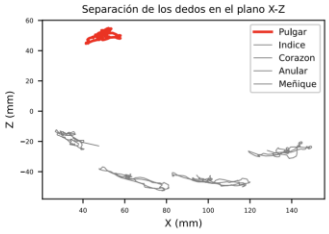
Mano Izquierda





Mano Derecha

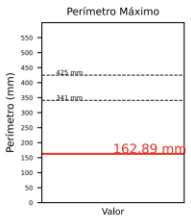


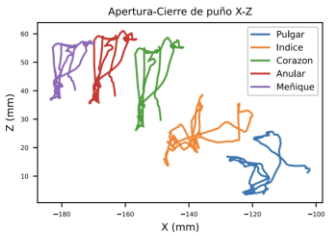


Ejercicio 4: Apertura - Cierre Puño

4.1 Perímetro máximo 'mm'

Mano Izquierda





Mano Derecha