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Circle Jump, A Novel Robotic Thumb Proprioception Assessment

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Mechanical and Aerospace Engineering

by

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# TABLE OF CONTENTS

# LIST OF FIGURES

Page

# LIST OF TABLES

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# ABSTRACT OF THE THESIS

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by

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Master of Science in Mechanical and Aerospace Engineering

University of California, Irvine, 2023

Professor David Reinkensmeyer, Chair

Thumb movement is critical for human hand function and often impaired by stroke. Despite the importance of the thumb, there are few assessments for evaluating the sensory ability of the thumb. The primary objectives of this thesis were to 1) develop a novel robotic assessment of thumb proprioception; 2) validate the assessment with neurotypical participants, focusing on how assessment parameters affect the measurement; and 3) validate the assessment with individuals who have had a stroke across multiple testing sessions. The thumb proprioception assessment we developed centers on a simple video game, called the Circle Jump game, which we implemented with the FINGER rehabilitation robot. In Circle Jump, the robot moves the visually-hidden thumb in a circle, and participants are prompted to press a button when the thumb aligns with a target location presented on a screen, using only proprioceptive feedback to estimate the actual thumb position in comparison to the target location. Two experiments were conducted to assess thumb proprioception using this game. The first experiment involved 26 neurotypical participants who engaged in the Circle Jump task six times in a single session, experiencing variations in speed, direction, workspace size, and the employed finger (thumb or index). The second experiment included 17 stroke survivors who engaged in the task seven times over a 2-month training program to measure potential improvements over time. Within this 2-month period, they also trained finger and thumb proprioception using other robotic games 3 times per week for 3 weeks. For the unimpaired participants, workspace size had little effect on thumb proprioceptive accuracy. Playing Circle Jump at a higher speed or employing the index finger to play modestly decreased error. In contrast, the history of exposure to a direction of rotation had a major effect on proprioceptive accuracy. Specifically, proprioceptive error exhibited a large and transient increase when the rotation direction was reversed after prolonged training in the original direction, mirroring patterns of motor adaptation that have been observed for reaching movements under external force fields. A new proprioception learning model is presented to account for this novel form of sensory adaptation. In the case of stroke survivors, mean thumb proprioception errors were approximately double those for the neurotypical population. Errors remained stable across the seven assessment sessions, showing only a small, nonsignificant improvement over this time. We conclude that the Circle Jump assessment is a valuable new tool for quantifying thumb proprioception. With it, we uncovered a novel form of sensory adaptation, quantified the effect of stroke on thumb proprioception, and found that a 3-week course of robotic training does not significantly improve thumb proprioception.

# 1. INTRODUCTION

The hand allows humans to perform a vast range of complex tasks and to interact with our environment in a dexterous and skillful way [1]. It is one of the most versatile grippers produced by nature, allowing us to securely grasp and manipulate a wide variety of objects of diverse morphologies [2].

The opposable thumb is an extraordinary anatomical trait of the hand and one of the distinctive features of human physiology over the majority of the animal kingdom. This trait is shared with a select group of animals, including gorillas, chimpanzees, and capuchin monkeys [3]. In comparison with the other fingers, the thumb has the largest cortical representation, both in the motor and in the sensory cortex [4]. It can produce the strongest forces of any of the fingers, is involved in more than 40% of hand functions and is given priority for replantation [5].

A wide variety of musculoskeletal and neurological diseases decrease the mobility of the human hand, including spinal cord injury, multiple sclerosis, cerebral palsy, arthritis and stroke. In the USA alone, over 19.9 million people present some sort of impairment in the upper body and have trouble in lifting or grasping [5]. Hand impairment deteriorates quality of life, limiting independence in activities of daily living (ADL).

Traditional rehabilitation for stroke survivors is usually focused on restoring walking capacity and functional use of the upper limbs. Despite comprehensive therapeutic interventions during rehabilitation, the likelihood of restoring functional use of the affected hand remains low. Three months post-stroke, merely 12% of stroke survivors show no difficulty with hand function, while 38% report significant challenges in hand functionality [6]. With the objective of increasing the amount of time and the intensity of the exercises devoted to hand rehabilitation both in the clinic and in the home environment, numerous groups have investigated the use of robotic devices as a supplement to traditional therapy approaches [7].

The human body is equipped with a vast array of sensors that facilitate motor control and movement. Proprioception, mediated by proprioceptors, is a critical sensory modality that enables humans to consciously monitor execution errors during motor skill acquisition, thereby enabling more effective movements. Proprioception, which pertains to the awareness of joint position in space, represents an elusive phenomenon, the underlying mechanisms of which remain unclear. In particular, the contribution of proprioception to motor learning and whether the brain processes proprioceptive information differently depending on the assessment and extremity is yet to be fully clarified.

## 1.1 Proprioception

Proprioception refers to the sense and perception of the body's position, movement, and orientation in space, as well as the awareness of the relative positions and movements of body parts. It involves the integration of sensory information from proprioceptors, specialized sensory receptors located in muscles, tendons, and joints, which detect changes in muscle length, tension, and joint angle. Proprioception plays a crucial role in motor control and coordination, allowing individuals to have a sense of where their body parts are without relying solely on visual feedback. It enables smooth and coordinated movements, helps maintain balance and posture, and contributes to a person's overall body awareness [8].

Proprioceptive training is an intervention designed to enhance proprioceptive function, ultimately aiming to improve or restore sensorimotor function. A growing body of empirical evidence supports the notion that targeted training of specific aspects of proprioception, such as position sense, not only improves the trained motor function but also exhibits potential transfer effects to non-trained motor tasks.

A systematic review on the effectiveness of proprioceptive training for improving motor performance showed that, across 70 included studies, proprioceptive training yielded similar improvements in both proprioceptive acuity (+46%) and motor performance (+45%) [9].

Another systematic literature review showed that, across 106 included studies, training specifically focused on proprioception yielded substantial effect sizes in proprioceptive assessments, proving to be significant across diverse populations and consistently comparable among different outcome measures [10]. In contrast, training without a specific proprioceptive focus resulted in moderate effect sizes, while no training demonstrated only modest or nonsignificant effect sizes. Across various outcome measures and participant demographics, proprioception-targeted training led to a mean improvement ranging from 23.4% to 42.6%, non-targeted training from 12.3% to 22.0%, and no training from 5.0% to 8.9% [10].

## 1.2 Stroke

Stroke, also known as cerebrovascular accident (CVA), is a medical condition characterized by the sudden interruption of blood supply to the brain, resulting in the impairment of brain function. It occurs when a blood vessel supplying oxygen and nutrients to the brain is either blocked by a clot (ischemic stroke) or ruptures (hemorrhagic stroke) [11]. The lack of blood flow to the affected region leads to the deprivation of essential nutrients and oxygen, causing brain cells to become damaged or die. The resulting neurological deficits can vary depending on the location and extent of the brain injury and may include symptoms such as paralysis, loss of sensation, speech impairment, cognitive impairments, and changes in behavior [11]. Stroke is a serious medical emergency that requires immediate medical attention and prompt intervention to minimize brain damage and facilitate recovery.

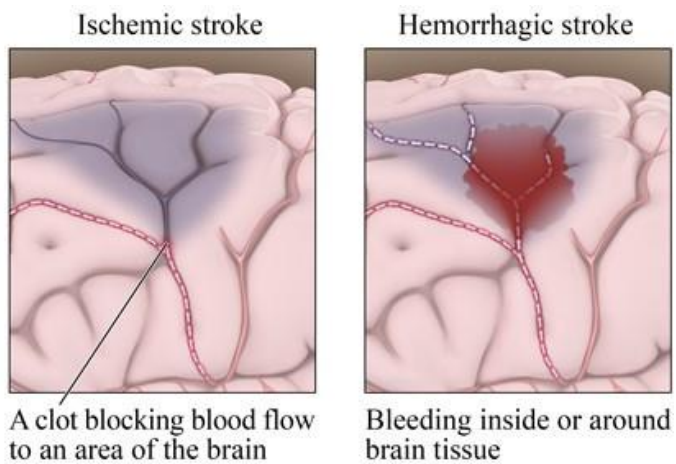



Figure 1: Ischemic vs. Hemorrhagic stroke graphical representation. Extracted from [12].

There are several risk factors that can increase the likelihood of having a stroke. These risk factors can be categorized into two main types: modifiable and non-modifiable [13].

- Non-modifiable risk factors:
    - Age: The risk of stroke increases with age, with the majority of strokes occurring in individuals over 65 years old.
    - Gender: Men have a slightly higher risk of stroke than women, although stroke can occur in both sexes.
    - Family history: Individuals with a family history of stroke are at a higher risk of experiencing a stroke themselves.
- Modifiable risk factors:

- High blood pressure (hypertension): Uncontrolled high blood pressure is a leading risk factor for stroke.
- Smoking: Cigarette smoking damages blood vessels and increases the risk of blood clots, making it a significant risk factor for stroke.
- Diabetes: Having diabetes increases the risk of stroke, particularly if blood sugar levels are poorly controlled.
- High cholesterol: Elevated levels of cholesterol contribute to the formation of fatty deposits in blood vessels, increasing the risk of stroke.
- Obesity: Being overweight or obese is associated with an increased risk of stroke. Physical inactivity: Lack of regular physical activity and a sedentary lifestyle can contribute to other risk factors such as high blood pressure, obesity, and diabetes, increasing the risk of stroke.
- Atrial fibrillation: This heart condition increases the risk of blood clots forming in the heart, which can then travel to the brain and cause a stroke.
- Excessive alcohol consumption: Heavy drinking can raise blood pressure and con- tribute to other risk factors for stroke.
- Drug abuse: Illicit drug use, particularly cocaine and amphetamines, can significantly increase the risk of stroke.

It's important to note that managing and controlling modifiable risk factors through lifestyle changes and medical treatment can help reduce the risk of stroke.

Proprioceptive deficits following a stroke can significantly impact an individual's ability to perceive and control limb position, leading to difficulties in motor coordination and functional activities [14]. Some of the consequences of stroke-related proprioceptive impairments include impaired limb awareness, coordination and balance problems, decreased motor control and accuracy, altered joint position sense and functional limitation in daily activities that rely on accurate limb positioning and movement, like dressing, reaching, grasping and manipulating objects, as well as difficulties with balance and walking [14].

Rehabilitation interventions, such as proprioceptive training and sensory reeducation, can play a crucial role in addressing these proprioceptive deficits following a stroke. These interventions aim to improve proprioceptive awareness, enhance motor control, and facilitate the reintegration of proprioceptive feedback into functional movements, ultimately supporting the recovery and rehabilitation of individuals after a stroke [15].

## 1.3 Thumb Representation in the Brain

The somatosensory cortex is the region of the brain responsible for processing and interpreting sensory information from the body, particularly related to touch, temperature, pain, and proprioception. It is located in the parietal lobe, and it is organized in a somatotopic manner, meaning that different body regions are represented in specific locations within the cortex. This organization is often referred to as the somatotopic map or homunculus. This cortex plays a vital role in our ability to perceive and discriminate tactile sensations and maintain body awareness and spatial orientation.

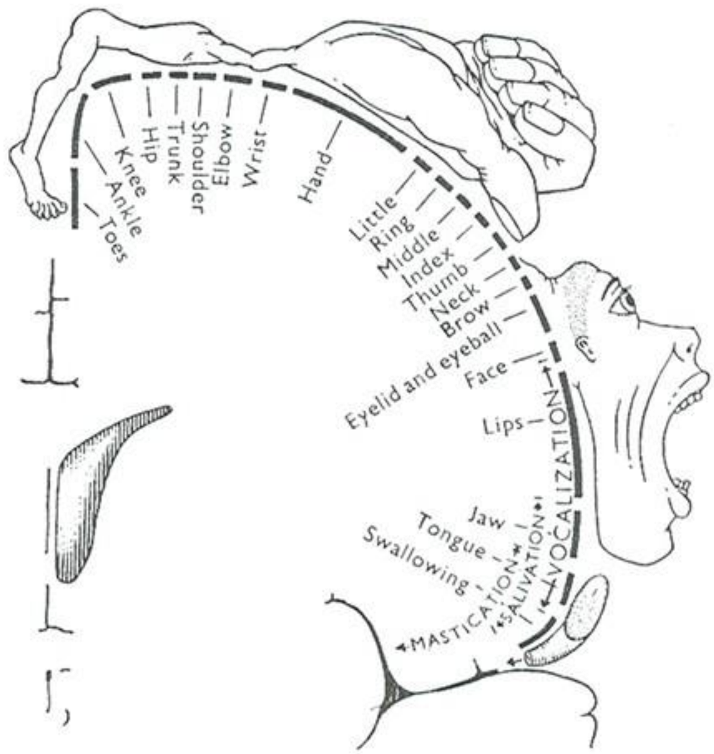



Figure 2: Somatotopic Homunculus. Extracted from [15].

Many studies have tried to figure out the exact positions where each part of the body is represented in the somatosensory cortex using functional magnetic resonance imaging (fMRI) and other brain mapping techniques [16], [17]. They have been able to demonstrate within-digit somatotopy in the primary sensorimotor cortex. Somatotopy refers to the precise mapping of a specific point on the central nervous system to a corresponding area of the body [17]. This is not so clear cut in the secondary sensorimotor cortex. Even though there is clear separation of more general body areas like the face, the hand and the foot; separate representation of the individual digits of the hand could not be shown [17]. The thumb is typically represented in a specific region of the somatosensory cortex, adjacent to the representations of other digits, such as the index and middle fingers. The somatosensory maps for individual fingers exhibited an organization extending across Brodmann areas (BAs) 3b, 1, and 2 (see Figure 3). This arrangement followed a lateral-to-medial and inferior-to-superior pattern, progressing from the thumb to the pinky [18]. Even though in most studies only one finger was stimulated at a time, the different digits appeared to share a varying amount of cortical space, showing some overlap [18].

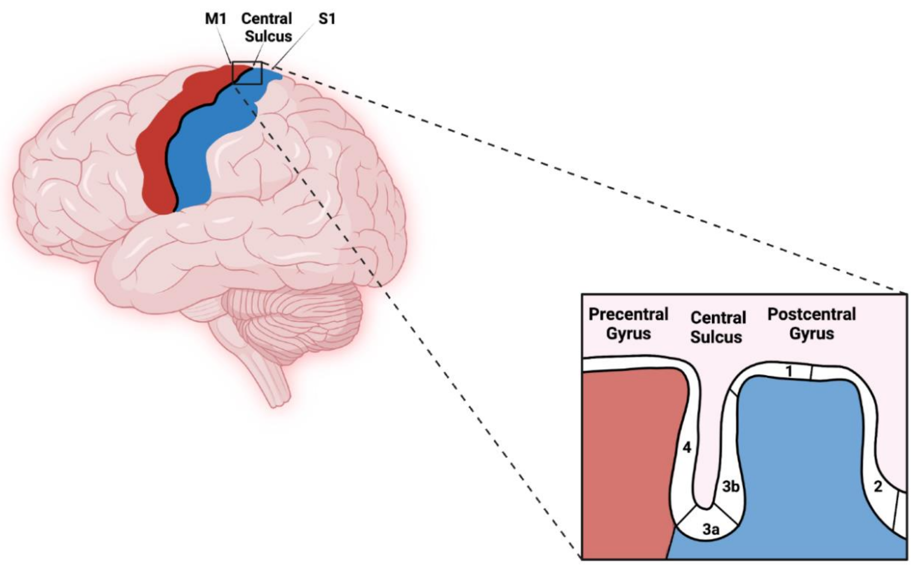



Figure 3: Lateral view of the primary somatosensory cortex (blue) and representation of Brodmann areas (BAs). Extracted from [18].

Furthermore, several studies discuss cortical magnification of the fingers, defining it as the relative size of the cortex activated corresponding to the relative receptive field size of the stimulated area. Receptive fields are defined areas where certain physiological stimuli can trigger a sensory neuronal response [19]. In the somatosensory system, these fields pertain to regions of the skin or internal organs. Larger receptive fields enable the detection of changes over a broader area but result in a less precise perception [19]. These studies revealed largest cortical magnification for the thumb and smallest for the ring and little fingers [18], [20]. The thumb was shown to have more cortex dedicated to its processing than the other four digits [21].

After the thumb, the finger that presented the larger representation was the index, it being the most used finger [22].

It's important to note that the somatotopic map of the somatosensory cortex can undergo changes due to plasticity, such as after injury or during learning and skill acquisition [23]. These changes can lead to reorganization and adaptive modifications in the representation of the thumb and other body parts in the somatosensory cortex. Somatotopic plasticity is thought to play a major role in stroke motor recovery [23].

## 1.4 Current Thumb Proprioceptive Assessments

The assessment of thumb proprioception in individuals who have experienced a stroke holds significant importance as it can offer valuable insights into the nature and magnitude of sensorimotor impairments resulting from the stroke in a part of the hand that is essential for daily function and is highly sensorial. Sensorimotor deficits in the thumb would be expected to manifest as challenges in perceiving thumb position, movement, and fine motor skills. Some studies have shown that the integrity of finger proprioception is one of the strongest predictors of the ability of the participants to benefit from therapy [24]–[26]. Hence, finger proprioception assessment can serve as a useful tool in comprehending the impact of stroke on sensorimotor functionality and guiding rehabilitation strategies.

Proprioception in the thumb is currently assessed in clinics using mainly three different methodologies [27]:

- Threshold to Detection of Passive Motion (TTDPM): The therapist moves the patient's thumb very slowly. The patient is instructed to indicate as soon as they sense the movement (threshold amount of motion required for detection) and direction (either flexion or extension) without using their vision. If they reported the direction incorrectly, the trial is discarded, and the testing continues until 3-5 correct judgements are achieved [27], [28].

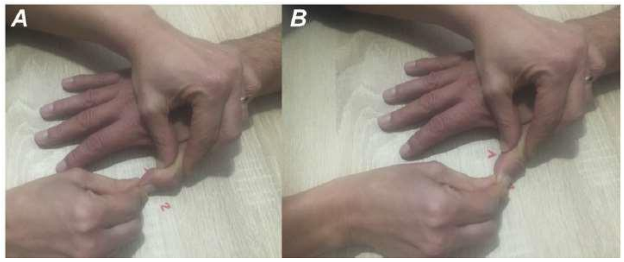



Figure 4: TTDPM for thumb proprioception assessment. Extracted from [27].

- Reproduction of Passive and Active Joint Position (RPJP and RAJP): The participant is presented with a target joint position, either passively or actively, for a brief duration. Subsequently, the joint is brought back to the initial position, either through active or passive means. Participants are then tasked with reproducing the target joint position [27], [28].


Figure 5: RAJP for thumb proprioception assessment. Extracted from [27].

RAJP is the most frequently used proprioception outcome measure in proprioception training studies [10]. Both TTDPM and RJP involve non-functional slow-speed movements that do not reflect real-life situations [28].

- Active Movement Extent Discrimination Assessment (AMEDA): Real-life movements can be used for proprioception assessment by performing various daily activities at natural movement speeds with objects that differ in thickness, strength, texture, or weight [27]. In one example protocol, participants were introduced to the locations of five positions for the thumb holding daily objects and engaged in fifty test trials. These trials involved the presentation of all five positions ten times in a randomized order. Following each encounter with a stopping position and returning to the starting point, participants assess and identify the position number (1, 2, 3, 4, or 5) for each test movement [28].


Figure 6: AMEDA for thumb proprioception assessment. Extracted from [27].

There are several challenges and limitations associated with proprioception assessments used in traditional therapy. Some of the problems include:

- Lack of standardized protocols: There is a lack of standardized protocols for proprioception assessments in traditional therapy. Different therapists may use different assessment methods, tools, or criteria, making it difficult to compare and generalize the assessment outcomes across different settings or studies. A systematic literature review on different possibilities for assessing proprioception found 32 different tests of proprioception across 57 analyzed research articles. These tests appeared to be sufficiently distinct in relation to claimed constructs, administration methods, and/or joints that they merited a separate classification [29].

- Limited sensitivity: Traditional proprioceptive assessments often lack the sensitivity to detect subtle proprioceptive impairments or changes in proprioceptive function. They may focus on gross measures of joint position sense or movement accuracy without capturing more subtle aspects of proprioceptive deficits.
- Lack of objective measurement tools: Traditional therapy often relies on subjective or semi-objective assessments that rely on clinician observation or qualitative scoring. Objective measurement tools, such as advanced technology-based sensors or motion capture systems, are not widely accessible or integrated into routine clinical practice, limiting the availability of precise and quantifiable proprioception assessments. Further research is required to establish reliability and validity as a starting point in the existing tests [29].

Addressing these problems in traditional proprioception assessments requires the development and integration of more standardized and sensitive assessment tools and protocols. Incorporating objective measurement technologies and considering functional contexts has the potential to enhance the accuracy and applicability of proprioception assessments in guiding therapy and tracking progress.

A novel, objective and standardizable thumb proprioceptive assessment is presented in this study.

# 2. METHODOLOGY

The two main tools used for this study are the FINGER robot and the Circle Jump game.

## 2.1 FINGER Robot

The Finger INdividuation Grasp Exercise Robot (FINGER) is an innovative finger curling robotic device custom-built by Prof. Eric Wolbrecht from the University of Idaho in collaboration with Prof. Reinkensmeyer's group at UCI [30] [14]. It employs a stacked configuration of single degree-of-freedom mechanisms to facilitate natural grasping patterns and enables subjects to explore a substantial range of motion in individual finger movements. Initially designed to assist the index finger and middle finger, the current version of FINGER has been enhanced to incorporate thumb movement as well [31] [32]. With its advanced control capabilities and backdriveability, the device offers high control bandwidth, making it suitable for assisting in precise timing tasks related to grasping.

FINGER operates within the natural range of motion of the fingers, following the comfortable trajectory of the middle and proximal phalanges during grasping. The orientation and position of the proximal phalanx, along with the position of the middle phalanx, are precisely controlled by dedicated 8-bar mechanisms for each finger. These mechanisms are actuated by high bandwidth, low-friction linear electric actuators, each with a single degree-of-freedom. Additionally, the device employs feed-forward control compensation to further reduce friction and optimize its performance [33]. The thumb's position is precisely controlled by a 2DOF spherical 5-bar thumb exoskeleton, which extends the functionalities of the FINGER device. The incorporation of the thumb module enhances the potential for comprehensive proprioceptive training and enables the evaluation of hand function across a wider range of movements.

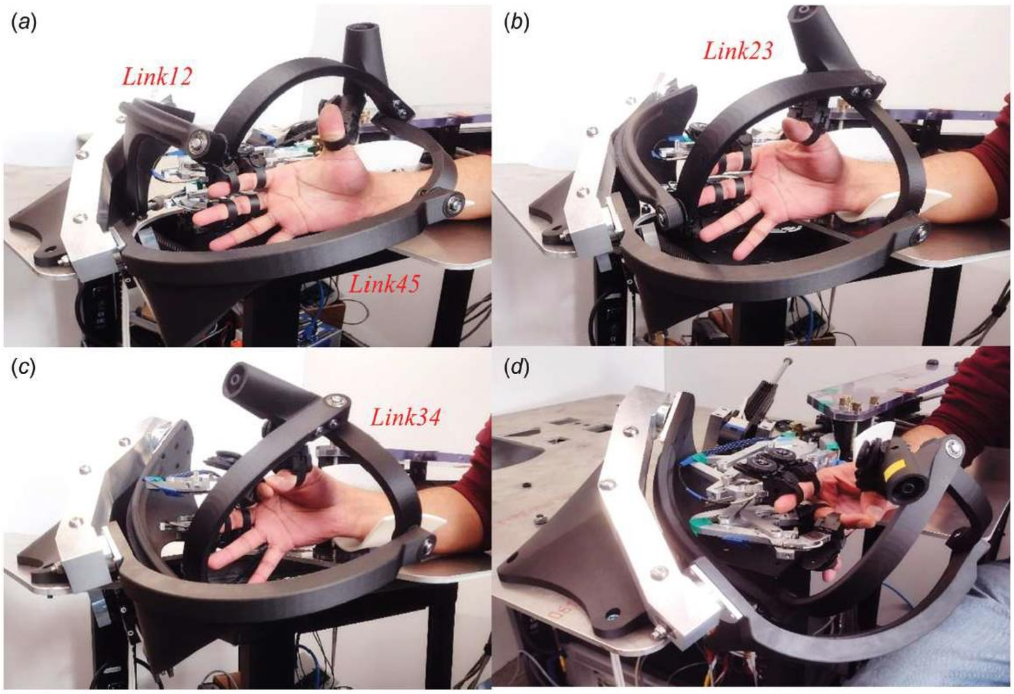



Figure 7: Subject's hand employing the FINGER device with the integrated 5-bar spherical thumb exoskeleton module. The depicted stages showcase the thumb's positioning and movement during various grasping scenarios. (a) The thumb is shown in the extended position. (b) The thumb assumes a partially grasping posture. (c) The index grasp is completed as the thumb meets the index finger. (d) The middle grasp is completed as the thumb meets the middle finger. Extracted from [32].

The FINGER robot has the capacity to train and assess each hand individually, but not simultaneously. Despite its symmetrical design, the actuators are not duplicated to avoid increased cost and complexity. To switch the actuators from right hand mode to left hand mode (see Figure 8), a flipping process of approximately fifteen minutes is required.

a) Right hand mode b) Left hand mode

Figure 8: Arrangement of the actuators on the FINGER robot.

## 2.2 Circle Jump Game

One notable feature of the FINGER is that has been integrated with various video games, such as GuitarHero [34] and Proprioceptive-Pong [35]. It can be easily incorporated into gaming experiences, providing tailored levels of assistance to accommodate individuals with varying degrees of hand impairment. In this section, we describe a new game for FINGER oriented at assessing and training thumb proprioception.

The FINGER had previously been used to evaluate proprioception in the index and middle fingers through the crisscross task [25]. In this task, the FINGER guides the participant's fingers in a crisscross motion, and they are prompted to press a button when they feel like their fingers are perfectly aligned or overlapped, without relying on vision. If we aimed to adapt this task for the thumb, it would require the use of two FINGER robots, allowing each thumb of the participant to be moved independently. As this was impractical, our exploration focused on identifying a game that would engage participants in utilizing thumb proprioception to gauge when it reached a designated target on a visual display.

Following an exploration of computer games suitable for assessing thumb proprioception, we settled on adapting a game known as Super Circle Jump. Originally designed for Android phones by *pixelclash* [36], this game involves the player triggering a jump when a ball, rotating around a circle, aligns with a visual target. We abbreviated its name to Circle Jump and modified the game to evaluate passive thumb proprioception using FINGER. This game was selected due to its compatibility with the crisscross task, with the distinction that instead of pressing a button when fingers intersect, participants press the button when the thumb reaches a visual target during rotational movement.

The code developed for this study was based on existing code provided by D. Reinsdorf [35]. D. Reinsdorf's implementation of the Proprioceptive-Pong algorithm served as the foundation for the Circle Jump code, which was developed using C++. By adapting the provided code, an implementation tailored to the unique requirements of the research was developed. Using this existing code significantly facilitated the progress of this work.

### 2.2.1 Game description

During gameplay, a white circle appears at the center of the screen, with a white ball rotating around it. The FINGER robot moves the player's thumb in a circular motion, mimicking the ball's movement on the screen. Following this, a new colored circle appears at a different location on the screen, as it can be seen in Figure 9.

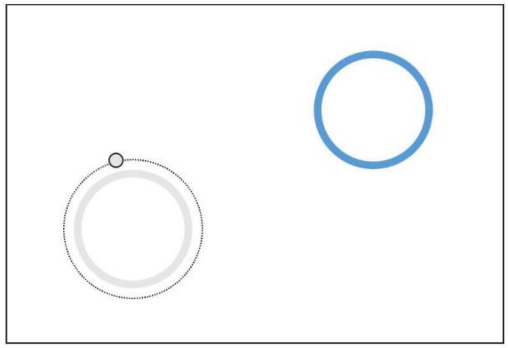


Figure 9: Representation of the target circle and the ball rotating.

The objective of the game is for the player to trigger a button when the ball is positioned between both circles, causing it to jump from the central white circle to the other. Upon pressing the button, the ball leaps radially from the initial circle. To intensify the proprioceptive challenge, one mode of the game restricts the player from visually tracking the ball's rotation around the first circle. In this scenario, the player must depend on their thumb's sensory perception to determine the appropriate moment to press the button. Thumb proprioception is evaluated by calculating the error between the angle at which the button is pressed and the optimal jump angle, which is determined by the line connecting the centers of both circles. See Figure 10 for a graphical representation of the jump condition.

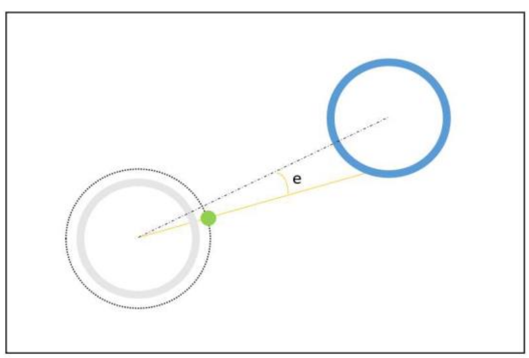



Figure 10: Jump condition and error (e) representation.

Following the button press, the player will have visual access to the trajectory of the jump. The trajectory will appear as a linear path if the ball is situated within the angular aperture that would prompt a collision with the second circle when jumping radially, denoting a successful shot. In contrast, if the ball is located outside of this range, it will execute a brief radial jump and begin orbiting around the initial circle at that distance until it reaches the optimal jump location - the line joining the centers of both circles - before finally proceeding to the next circle. This outcome is considered an unsuccessful shot. See Figure 11 for a graphical representation of these two phenomena.

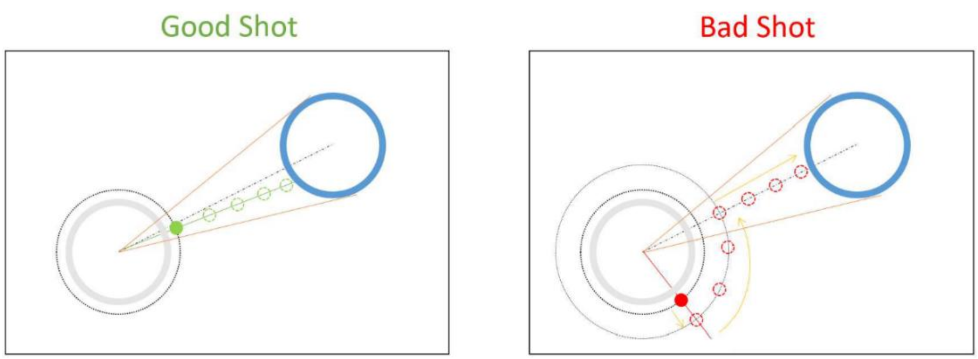



Figure 11: Jump conditions depending on when the button was pressed.

### 2.2.2 Versions of the game

The game Circle Jump can be played in two different game modes:

- Video only: The player can see the position of the ball at all times. It does not require any proprioception sensing since vision overrides it [37].
- Propriopixels: This is a concept developed in the Dr. Reinkensmeyer's lab where the information required to make gameplay decisions is provided to the user through their proprioception sensors instead of through pixels on the screen [38]. This is the proprioceptively challenging assessment, where the player cannot see the position of the ball on the screen while it is rotating

around the white circle but has to rely on the feeling of where their finger is in order to know when to press the button. Once the button has been pressed the player might be able to see the jump trajectory or not, depending on the feedback option selected.

### 2.2.3 Game options

Other parameters that can be changed in the game are the following.

- Hand: Right or Lett. As stated before in Section 2.1, the FINGER robot can be flipped and be used with either the right or left hand. This parameter selects which hand is being used by the participant. For unimpaired participants, this will be their dominant hand, while for stroke patients it will be their impaired hand.
- Finger: Thumb or Index. This selects the finger that will be placed in the thumb portion of the device. The game is mainly designed to be used to assess thumb proprioception, but the FINGER robot allows for the index finger to be placed in the thumb's position and assess its proprioception using the Circle Jump game.
- Direction: Clockwise or Counterclockwise. This selects the direction at which both the ball and the thumb will rotate around the white circle.
- Speed: Slow, Medium or Fast. This selects the speed at which the ball and the thumb will rotate around the white circle.
- Workspace size: Big or Small. This selects the radius of the circular trajectory that the thumb will follow to rotate around the white circle. It does not change the radius of the white circle on the screen.

- Feedback:
    - None: The player does not see the ball at any point nor the jumping trajectory. The player does not get any feedback regarding the position of the ball when the button is pressed either.
    - Hit/Miss: The player does not see the jumping trajectory but gets a message saying if the ball hit the target circle (Good shot) or if it missed it (Bad Shot).
    - Error: The player does not see the jumping trajectory but can see a number that shows how close the shot was to the optimal jump angle. This number represents the distance between where the ball was when the button was pressed and the optimal jump angle. The score will be closer to O if the ball was close to the optimal jump angle and closer to 100 if it was far away from the target circle.
    - All: The player can see the jumping trajectory and will get a score from +0 to +10 for each jump, which keeps adding to the total score for that game. A +10 will be given when the error is very low.

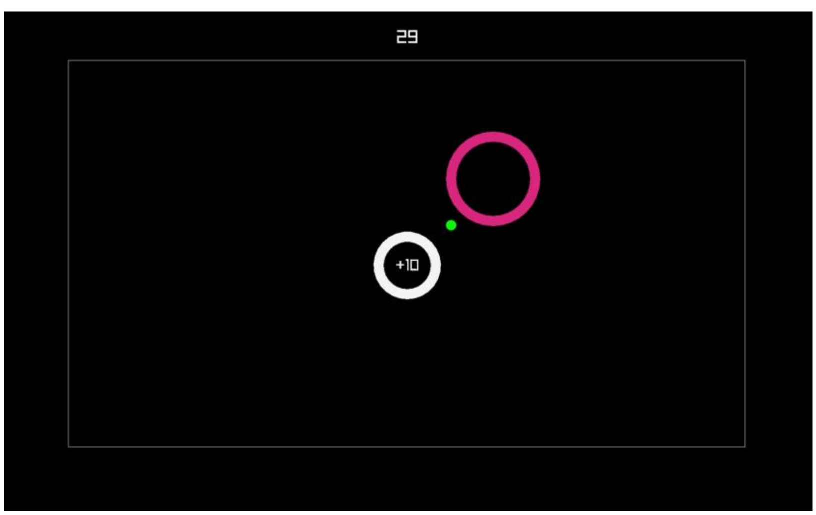



Figure 12: All feedback option for perfect jump (+10 points).

- Visibility: Covered or Uncovered. The FINGER robot has a black screen that can be used to cover the visibility of the hand by the user. This parameter represents whether the hand is visible by the player and therefore no proprioception is being used or if the hand is covered and therefore the player will have to rely on their proprioception to know the position of their thumb and decide when to press the button. Uncovered games are used to train participants and to make sure they understand how the game works, while the proprioceptive assessment is done in covered mode. Furthermore, uncovered games only have 10 jumps while covered ones have 20 jumps.

All these parameters can be changed in the game's menu before the game starts, see Figure 13.


Figure 13: Menu options.

## 2.3 Experimental Design

For this thesis, the Circle Jump game was used to assess thumb proprioception in two different experimental studies, one involving neurotypical participants, and the other involving participants with stroke as a part of a clinical trial testing the effectiveness of proprioceptive training.

### 2.3.1 Assessment of thumb proprioception in neurotypical participants

The aim of this investigation was to assess thumb proprioception, as well as the correlation between proprioceptive acuity in the distal extremities, namely, the fingers and ankles, in unimpaired young and old participants. The study comprised two sessions separated by a 3-10 day interval, with each session evaluating proprioception in either the hands or ankles. To counterbalance the order of assessments, participants were randomly assigned to undergo the ankle or hand session first, thereby ensuring order balance across the entire cohort. Additionally, the order of assessments performed within each session was randomized between participants and sessions to mitigate the impact of task order on task performance. No further blinding or stratification was employed.

The inclusion criteria for this study were the following:

- Young group: Adults 18-40 years old, able to read and speak English.
- Old group: Adults 50-88 years old, able to read and speak English.

The exclusion criteria were:

- History of neurological injury.
- Current injuries that affect the ability to move or feel either fingers of the dominant hand and/or ankles.

- Currently pregnant.

Several tests were performed to assess proprioception of the ankles, fingers, and thumb. This thesis focuses exclusively on the thumb, therefore the details of the assessment performed for the thumb are provided below.

Thumb Proprioception Assessment with Circle Jump: In this assessment, individuals play the Circle Jump gamed with their passive thumb. The thumb component of the FINGER robot moves the thumb in a circular motion and the participant indicates with a button when it is aligned with a location on the computer screen indicated by the game. For the experiment described in this thesis, we varied the speed of thumb rotation, the workspace of rotation, and the direction of rotation to examine the effect of these parameters on thumb proprioception acuity. Each assessment has 20 jumps and takes between 2 and 10 minutes, depending on the rotational speed and on how much time each participant takes to press the button.

- Slow Rotational Speed, Full Workspace, Clockwise Rotation, Thumb: 30 deg/s.
- Medium Rotational Speed, Full Workspace, Clockwise Rotation, Thumb: 60 deg/s.
- Fast Rotational Speed, Full Workspace, Clockwise Rotation, Thumb: 120 deg/s.
- Medium Rotational Speed, Full Workspace, Counter-Clockwise Rotation, Thumb: 60 deg/s.
- Medium Rotational Speed, Reduced Workspace, Clockwise Rotation, Thumb: 60 deg/s.
- Medium Rotational Speed, Full Workspace, Clockwise Rotation, Index (see Figure 14): 60 deg/s.

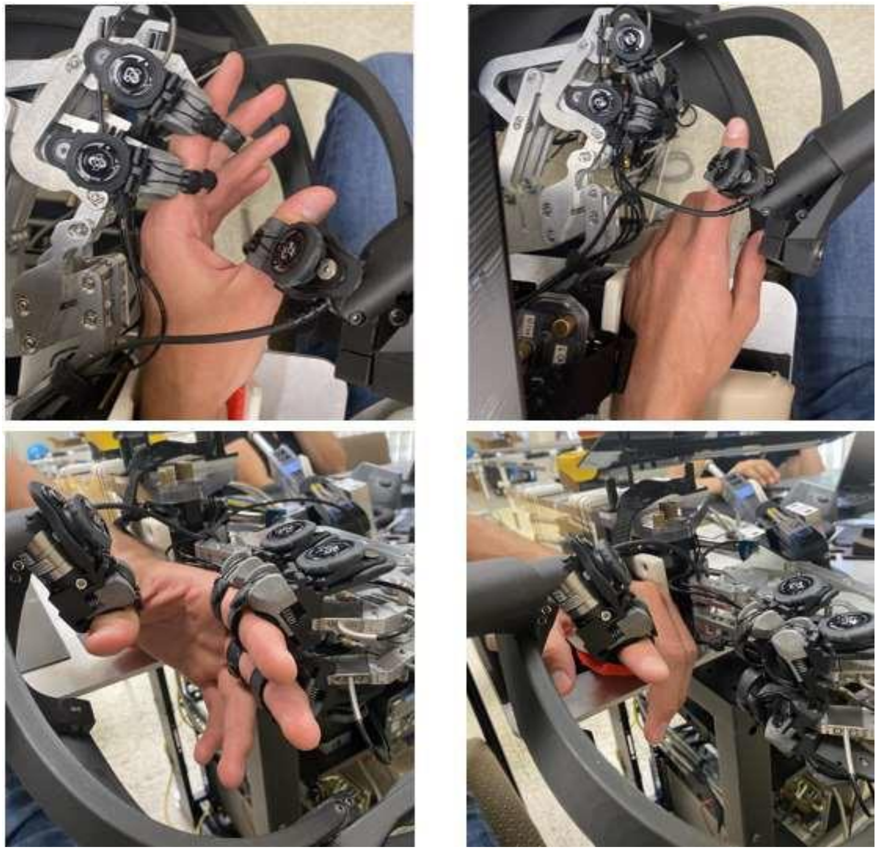


Figure 14: Left: Thumb placement. Right: Index finger placement.

This information is summarized in Table 1.

| Game# | Speed | Direction | Workspace | Finger |
|---|---|---|---|---|
| 1 | ***Slow*** | Main | Ful | Thumb |
| 2 | ***Medium*** | Main | Full | Thumb |
| 3 | ***Fast*** | Main | Full | Thumb |
| 4 | Medium | ***Opposite*** | Full | Thumb |
| 5 | Medium | Main | ***Half*** | Thumb |
| 6 | Medium | Main | Full | ***Index*** |

Table 1: Game parameters.

### 2.3.1 Assessment of thumb proprioception in participants with a chronic stroke

This is a randomized, single-blinded controlled trial currently underway to determine the role of somatosensory input in robot-assisted hand motor rehabilitation after stroke.

A total of 60 individuals with single or multiple ischemic or hemorrhagic stroke, confirmed radiologically, exhibiting residual unilateral hand weakness, and at least 6 months post- stroke, are being recruited to participate in the study with 33 enrolled so far.

The inclusion criteria for this study are the following:

- Adults, 18-85 years of age.
- Experienced a single or multiple, ischemic or hemorrhagic stroke, with unilateral weak- ness, at least six months previously.
- Ability to score at least 3 blocks on the Box and Block Test. BBT score of the affected arm is at least 20% worse than that present with the unaffected arm.
- Absence of major depression, as defined by DSM V criteria or a score on the Geriatric Depression Scale < 10.

The exclusion criteria are:

- Any substantial decrease in alertness, language reception, or attention.
- Severe muscle tone at the upper extremity (score > 3 on the Modified Ashworth Spasticity scale)
- Severe aphasia (score of 3 on the NIH stroke scale (question 9)).
- Pregnant or lactating.

- Advanced liver, kidney, cardiac, or pulmonary disease.
- Plans to alter any current participation in other rehabilitation therapy in the time period of the study.
- A terminal medical diagnosis consistent with survival < 1 year.
- A history of significant alcohol or drug abuse in the prior 3 years.
- Current enrollment in another study related to stroke or stroke recovery.
- Any other medical contraindication to participation in the study, as evaluated by our team physician.

The participants are being randomly assigned to three different groups: Group 1 - Visual games with physical assistance; Group 2 - Visual games with virtual assistance; Group 3 - Proprioceptive games with physical assistance. All groups are receiving robotic training through the FINGER robot three times a week for three weeks. Each session lasts approximately 120 minutes and takes place at the iMove Collaboratory, supervised by trained study personnel.

Throughout the study, all participants undergo four evaluations conducted by a blinded evaluator: two baseline evaluations scheduled 5 to 10 days apart, a post-intervention evaluation after the three weeks of exercises with the FINGER robot, and a one-month follow-up evaluation. Additional assessment visits are arranged as needed based on participants' endurance or fatigue levels. In total, participants have four clinical assessment visits for the study. Each evaluation lasts approximately 2 to 2.5 hours.

The participants' thumb proprioception is assessed using the Circle Jump game in both baseline visits, in the second training sessions each week, in the post therapy visit and in the one-month follow-up, for a total of seven times. During each assessment, participants play four games. All of them are played at medium speed, full workspace and in the clockwise direction of rotation. The first game is played with vision of the little white ball and vision of their thumb (Display mode: Video Only and Visibility: Uncovered). For the second game, the graphical image of the ball is removed from the game so the participants cannot see the ball but still have vision of their thumb (Display mode: Propriopixels and Visibility: Uncovered). The last two games are without vision of either the ball or their thumb (Display mode: Propriopixels and Visibility: Covered). The first two games are used to teach or remind them of how the game is played, while the last two games are the assessments that were analyzed to quantify proprioception.

# 3. RESULTS - Neurotypical Study

In the Circle Jump game, proprioceptive acuity is quantified by "jump error", which is the difference between thumb and target location when the participant pushes the button. We analyzed jump errors for unimpaired participants, comparing how jump errors varied with thumb speed, rotation direction, workspace size, and with finger used (thumb versus index finger).

## 3.1 Task Order Dependence

The order in which each participant played the six different games was randomized. We first checked if there was a dependence on the order in which the different games were played; for example, participants may have performed better on the sixth game compared to the first game. The absolute angular error for each participant in relation to the order in which they performed the tasks can be seen in Figure 15.

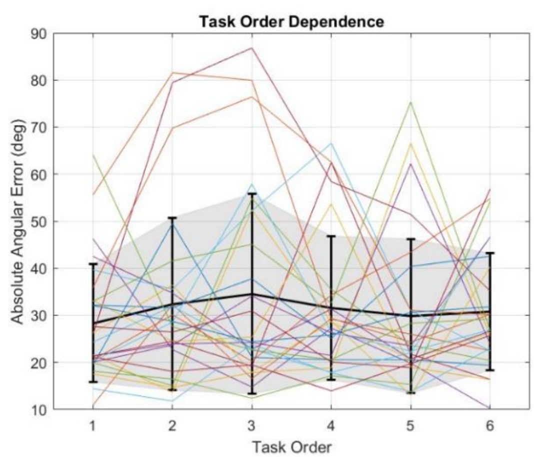



Figure 15: Absolute angular error depending on task order.

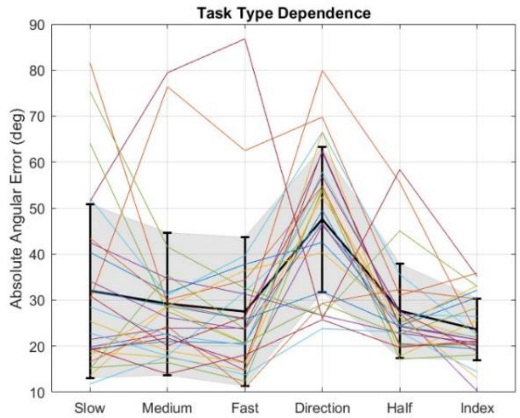
There was not a significant dependence on order (ANOVA, $p = 0.91$) and no learning was evident from playing six games in a row (paired t-test, $p = 0.22$).

## 3.2 Task Type Dependence

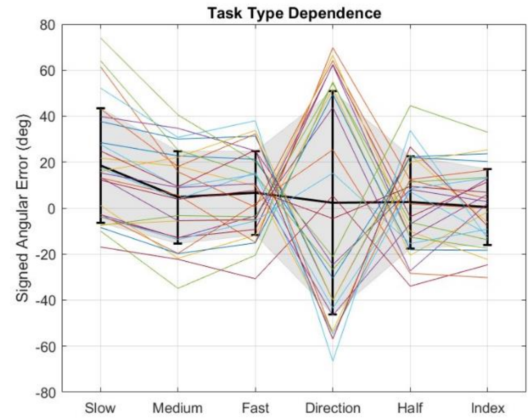
We defined the "baseline task" as when participants played Circle Jump at medium speed, with half of the participants performing in a clockwise (CW) rotation direction and the other half in a counterclockwise (CCW) direction. Additionally, the full workspace was used, and participants used their thumb (as opposed to the index finger) for the tasks. Each variant of the baseline task altered one of these features. For instance, the following tasks were administered to the participants who experienced CW as their primary direction (and for the other half who experience CCW as the primary direction, one may exchange CW and CCW below):

- Task 1: **Slow** speed, CW direction, Full workspace, Thumb
- Task 2: **Medium** speed, CW direction, Full workspace, Thumb
- Task 3: **Fast** speed, CW direction, Full workspace, Thumb
- Task 4: Medium speed, **CCW** direction, Full workspace, Thumb
- Task 5: Medium speed, CW direction, **Half** workspace, Thumb
- Task 6: Medium speed, CW direction, Full workspace, **Index**

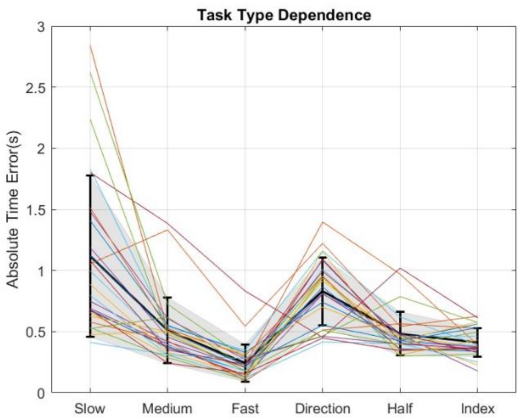
The absolute and signed angular and time errors for the different tasks can be observed in Figure 16. We analyzed each parameter separately as follows.



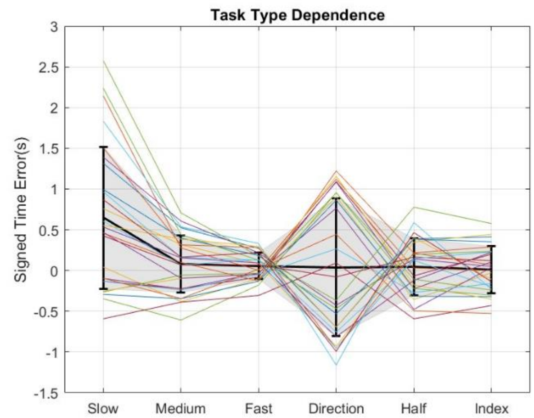

a) Absolute angular error




b) Signed angular error




c) Absolute time error

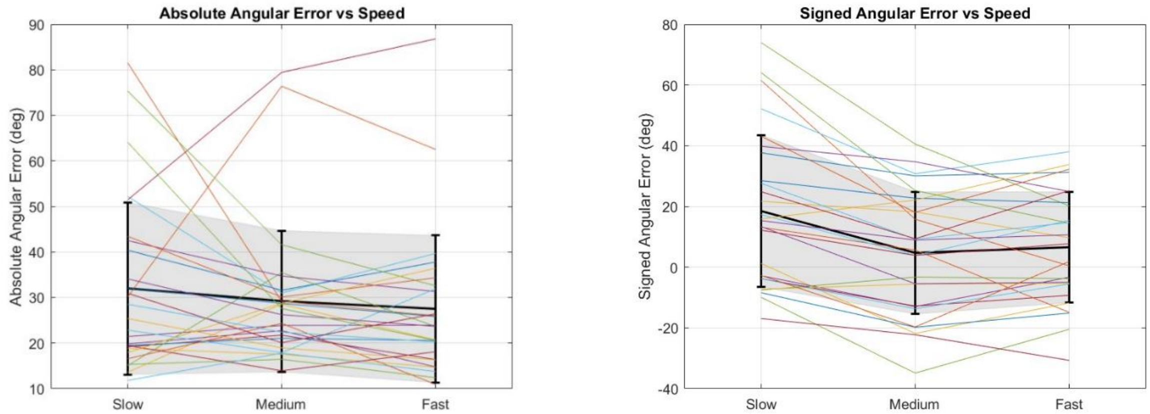



d) Signed time error

Figure 16: Error depending on task type.

## 3.3 Speed Dependence

The only difference between tasks 1, 2 and 3 was the speed at which the thumb rotated. The absolute and signed angular errors in those three tasks can be observed in Figure 17.




a) Absolute angular error

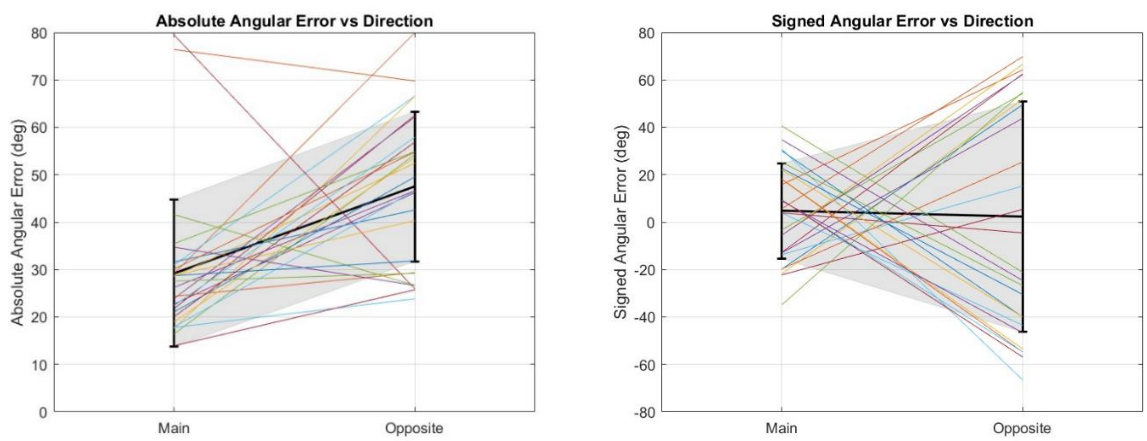
b) Signed angular error

Figure 17: Angular error depending on speed.

The signed angular error decreased significantly at higher speeds (ANOVA, p = 0.03), while the absolute angular error did not significantly change (ANOVA, p = 0.3).

## 3.4 Direction Dependence

The only difference between tasks 2 and 4 was the direction of rotation of the thumb. The absolute and signed angular error in those two tasks can be observed in Figure 18.



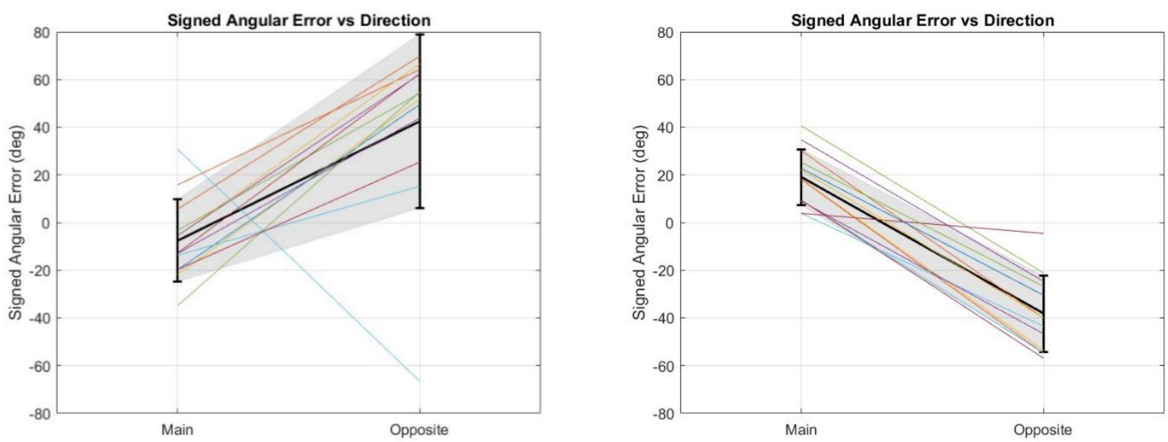

a) Absolute angular error

b) Signed angular error

Figure 18: Angular error depending on direction.

The absolute angular error increased significantly after changing the direction of rotation (paired t-test, $p < 0.001$), while the signed angular error did not significantly change (paired t-test, $p = 0.78$).

On the one hand, it can be seen in Figure 18a that the absolute angular error significantly increased when changing directions. On the other hand, when looking at Figure 18b one might think that there is no dependence after changing directions for the signed angular error, since the p-value is very high. However, two very distinct trends can be seen in this Figure 18b. To check this phenomenon, Figure 18b was divided into the two groups for the study.




a) Signed angular error for main CW group

b) Signed angular error for main CCW

Figure 19: Signed angular error depending on direction divided into the two groups.

In Figure 19a one can find the signed angular error for the participants that played most games in CW as their main direction and then had one single game in CCW as their opposite direction, while in Figure 19b one can find the signed angular error for the participants that played most games in CCW as their main direction and then had one single game in CW as their opposite direction. Both differences are significant (paired t-test, $p = 0.0023$ for CW group; paired t-test, $p < 0.001$ for CCW group).

It can be seen in this Figure 19 that the participants who started playing in CW direction had a higher signed angular error after changing directions, which means that they started triggering the jump earlier than before. In contrast, the participants who started playing in CCW direction had the opposite effect, with the signed angular error decreasing after changing direction, which means that they triggered the jump later than before. This means that participants tended to press the button late in CW direction and early in CCW. The only participant in Figure 19a that was going early in CW and then started going late for CCW (light blue line) was the only left-handed subject in the study, which leads to the presumption that there might be some sort of anatomical feature that makes the participants go late when the thumb is going down closer to the palm of the hand and early when it's going up closer to the palm, regardless of what hand is being used.

### 3.4.1 Learning after changing directions

Five out of the six tasks were performed in one direction, and one was performed in the opposite direction. To analyze how this change affected performance, all the jump trials for an example participant were plotted. Figure 20 shows the absolute angular error for each single jump that one subject performed, divided into the 6 games they played. The dark blue lines represent the errors for the games in the main direction (CW) and the light blue line represents the errors for the game in the opposite direction (CCW).

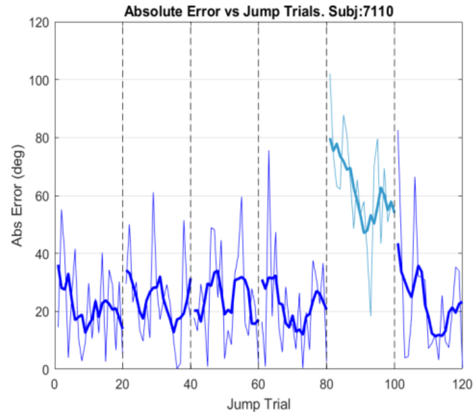
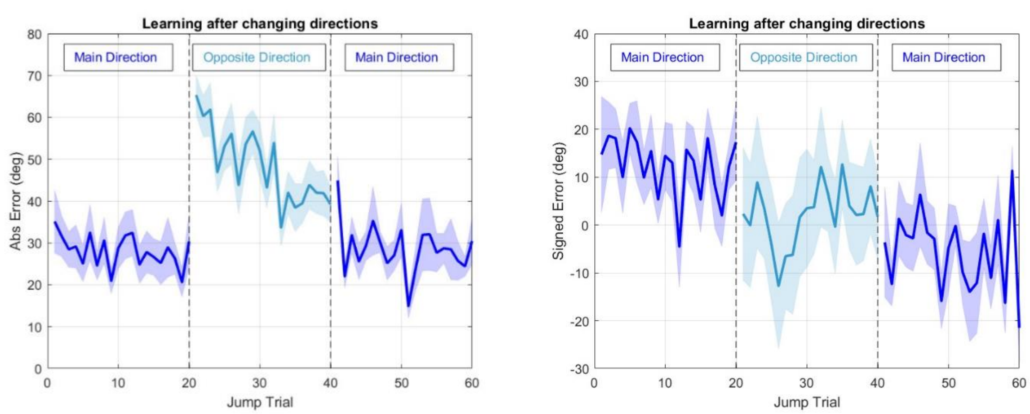



Figure 20: All absolute angular errors vs. jump trial for an example subject.

It can be appreciated that after playing four games in the main direction, when the rotation direction is changed, the absolute angular error increases considerably and the error remains larger than the one observed during the original direction throughout the entire game. Upon returning to the original rotation direction, the error initially remained high for the first few jumps but gradually reverted to the level seen before the direction change occurred.

After performing this analysis for one subject, the same test was conducted for all subjects, focusing on the games right before, during, and right after changing the rotation direction. Figure 21a illustrates the impact of this phenomenon.




a) Absolute angular

b) Signed angular error

Figure 21: Learning after changing directions.

Regarding the absolute angular error, it can be seen in Figure 21a that there was a significant difference between jump trials 20 and 21, with the mean absolute error for all participants being more than twice as large for trial 21 with respect to trial 20 (paired t-test, $p < 0.001$). That error then decreased along the duration of the game in the opposite direction, showing significant learning in a single game, going from trial 21 to trial 40 ($p < 0.001$). There was not a significant difference between trials 20 and 41 ($p = 0.24$), which are the last jump in the main direction before changing it and the first jump in the main direction after.

Concerning the signed angular error, a similar effect to the one depicted in Figure 18b can be seen in Figure 21b, as each group exhibits an opposing pattern. When averaging both groups, the directional effects negate each other.

As it was previously done, Figure 21b was divided into the two different groups regarding the main direction of rotation to see the learning process in both directions. The same pattern seen in Figure 21a can be seen in Figure 22, however this time the main CW group (blue) started pushing the button substantially earlier when the direction was changed and then went back to pushing the button late, while the main CCW group (red) started going later when the direction was changed and then way early when it was reversed to the original one.

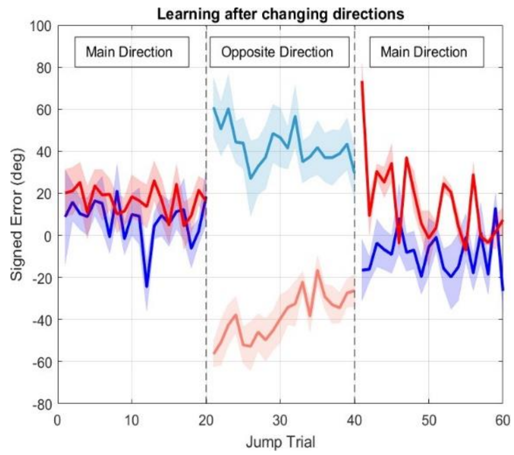
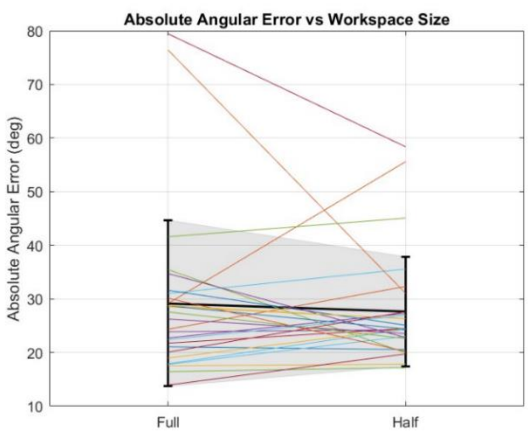



Figure 22: Learning after changing directions - Signed error.

## 3.5 Workspace Size Dependence

The only difference between tasks 2 and 5 was the size of the circumference that the thumb was following. The absolute and signed angular error in those two tasks can be observed in Figure 23.




a) Absolute angular error

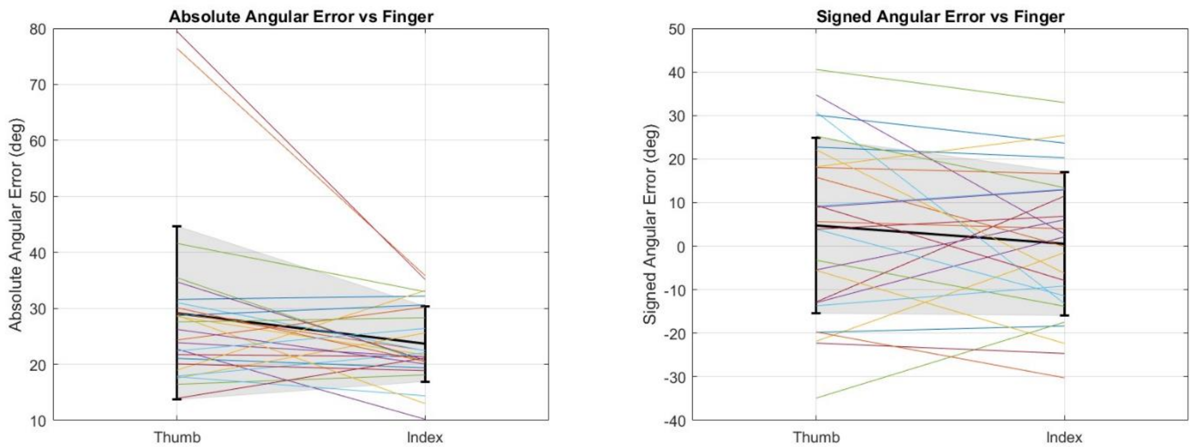

b) Signed angular error

Figure 23: Angular error depending on workspace size.

There was no significant difference between playing the game with the full workspace or with the half workspace ($p = 0.73$ for the absolute angular error and $p = 0.37$ for the signed angular errors).

## 3.6 Finger Dependence

The only difference between tasks 2 and 6 was that in task 2 the thumb was rotated and in task 6 the index finger was rotated. The absolute and signed angular error in those two tasks can be observed in Figure 24.




a) Absolute angular error

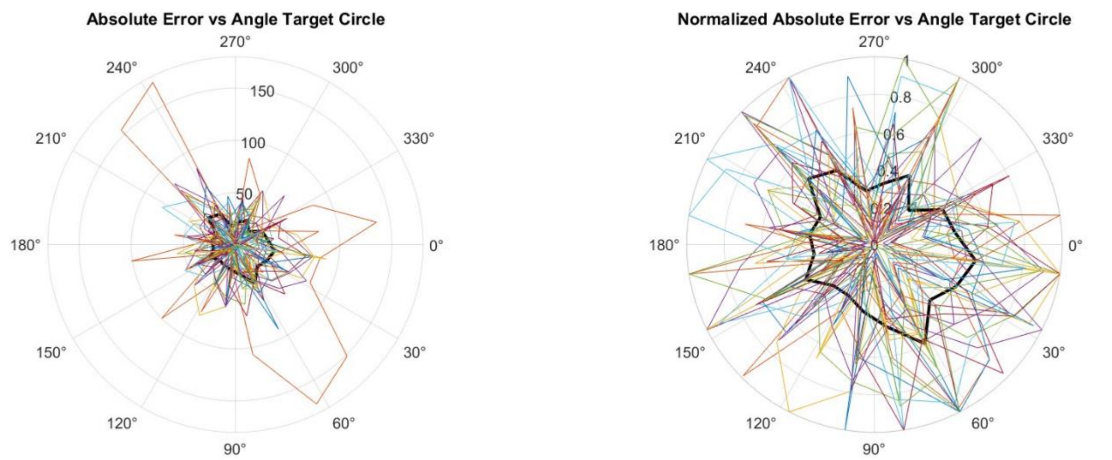
b) Signed angular error

Figure 24: Angular error depending on finger.

Participants performed significantly better using the index finger for the absolute angular error (paired t-test, $p = 0.046$) but not the signed angular error (paired t-test, $p = 0.2$).

## 3.7 Quadrant Dependence

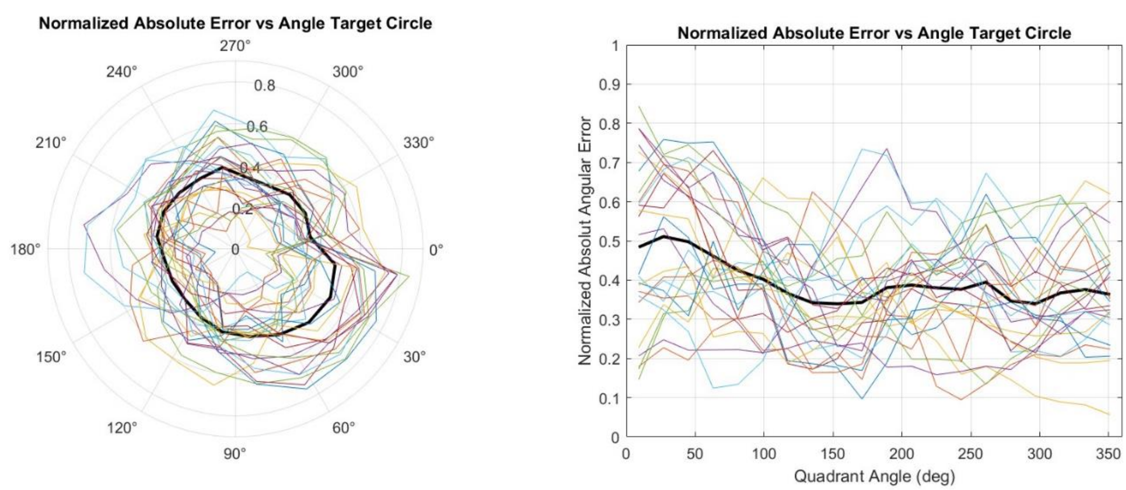
In order to assess if there is a specific region of the workspace where thumb proprioception is worse, all the errors for one game were plotted in relation to the angle of the target circle. As it can be seen in Figure 25a, the fact that some participants had bigger errors than the others obscures the desired angular dependent results. For that reason, the errors for all participants were normalized from 0 to 1. This can be seen in Figure 25b.




a) Absolute angular error b) Normalized absolute angular error

Figure 25: Absolute angular error for quadrant dependence.

In order to smooth the data in Figure 25b, the *movmean()* MATLAB function was used on each participant's errors and then the mean was computed again from the smoothed data. The resulting plots can be found in Figure 26 both in polar and Cartesian coordinates.




a) Polar plot b) Cartesian plot

Figure 26: Normalized and filtered absolute angular error for quadrant dependence.

There are some regions where the error is larger, and that area is the one where the thumb is closest to the palm of the hand. There is a significant difference between the errors at angle 27° (highest mean error) and the errors at angle 153° (lowest mean error) (paired t-test, $p = 0.0022$)

## 3.8 Summary

In summary, using the Circle Jump game we found that thumb proprioceptive error experiences a substantial increase when altering the direction of thumb rotation, regardless of the initial direction. Additionally, we observed a significant but small speed dependence, with the error diminishing at higher speeds. Furthermore, a slight finger dependence was evident, indicating that the error was lower when using the index finger rather than the thumb for the assessment. Lastly, there was a significant angular dependence, with the error being larger in the quadrant where the thumb was closest to the palm of the hand.

# 4. RESULTS – Stroke Study

As discussed in Section 2.3.2, the evaluation of thumb proprioception for the stroke survivors occurs at seven different time points during the training process. The initial two assessments take place during the baseline visits (BL1 and BL2) before the training begins. The subsequent three assessments occur during the second session of each of the three weeks of training (W1, W2 and W3), followed by the last two assessments during the post-therapy (PT) session and the 1-month follow-up (FU) session.

Up to this point, 33 participants have been recruited for the study. However, Circle Jump was incorporated as a thumb proprioception assessment after the 11th participant, and the data for the last 5 participants is still pending collection. Consequently, the data presented below encompasses a total of 17 participants.

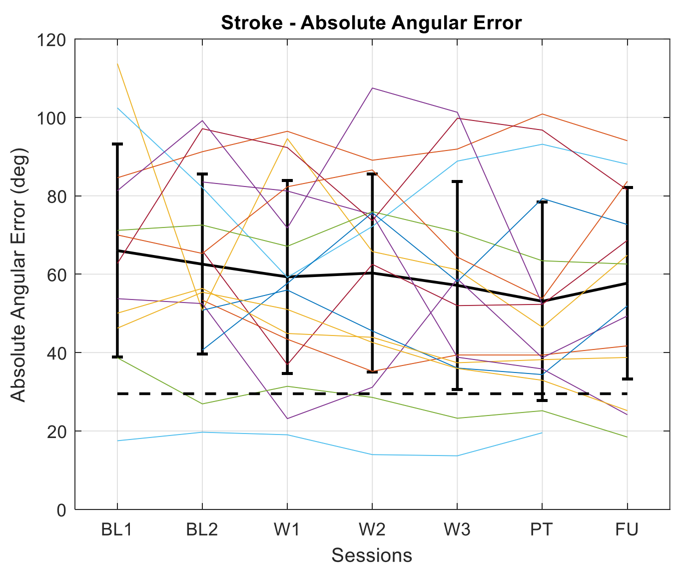



Figure 27: Absolute angular error along training for all participants. Each colored line represents a single participant, and each point on the line represents the average absolute error for all jumps performed during that session. The thicker black line indicates the mean and standard deviation for each session. The dashed black line represents the baseline mean absolute angular error for the unimpaired participants.

Figure 27 displays the average absolute error for each session. There was a small reduction of angular error across the training period. The average absolute error on BL1 was 66.01°, which decreased to 53.09° after completing all training sessions (PT) and slightly increased to 57.70° after the 1-month follow-up (FU). However, this decrease was not significant (paired t-test comparing the start of the training (BL) to the end (PT), $p = 0.15$; and comparing BL to the one-month follow-up (FU), $p = 0.2$).

When comparing the stroke patients with the unimpaired participants, we can see that the mean absolute angular error is significantly larger (approximately twice as large) for the stroke patients at BL1 (paired t-test, $p < 0.001$) and also at PT (paired t-test, $p = 0.0014$).

## 4.1 Comparing Groups

Throughout the three-week training period, only participants in Group 3 (proprioceptive games with physical assist) engage in a unique challenge that focuses on enhancing their proprioception in the thumb, index, and middle fingers. This is achieved by playing the Proprioceptive-Pong game and the Guitar Hero game. During the Proprioceptive-Pong game, they specifically target the proprioception of their index and middle fingers. However, during the Guitar Hero game, the emphasis shifts to improving their thumb proprioception. In this game, the FINGER robot moves their thumb to three distinct positions (top, middle, and bottom), and participants must rely on their sense of thumb position to determine which finger to flex in order to hit designated targets. The Circle Jump assessment can effectively gauge the extent to which playing this game contributes to the improvement of thumb proprioception.

The data presented in Figure 27 can be categorized into the three different groups. The corresponding plots for each group can be observed in Figure 28, Figure 29 and Figure 30.

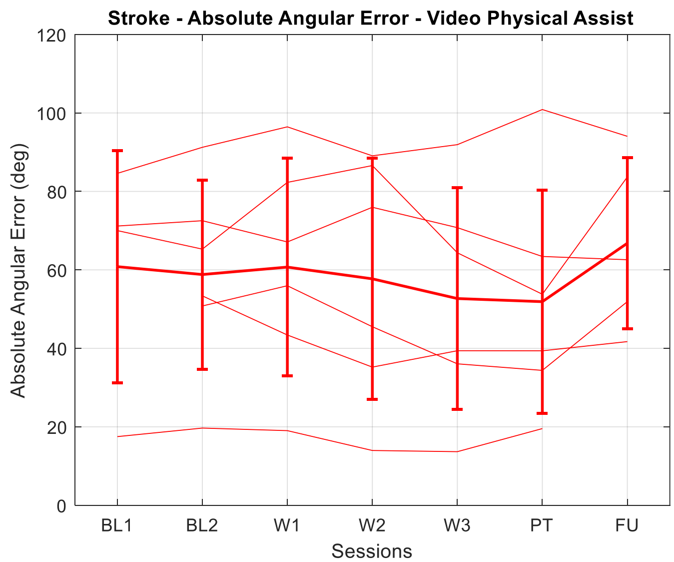



Figure 28: Absolute angular error along training for Group 1 - Video Only with Physical Assist.

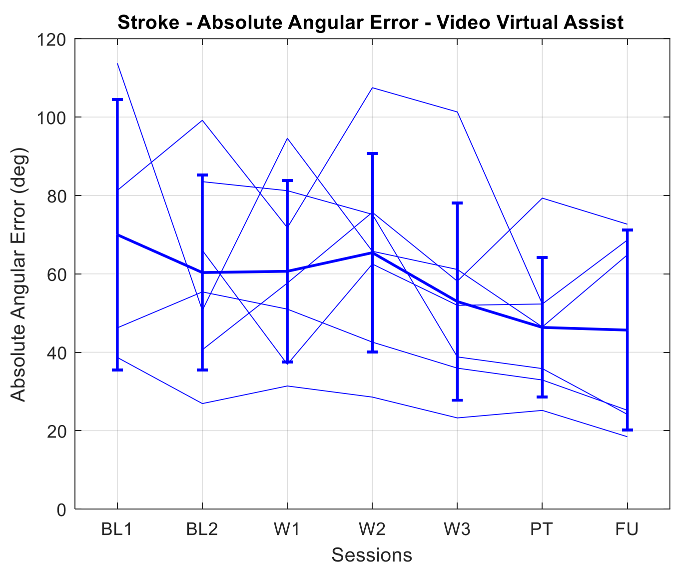



Figure 29: Absolute angular error along training for Group 2 - Video Only with Virtual Assist.

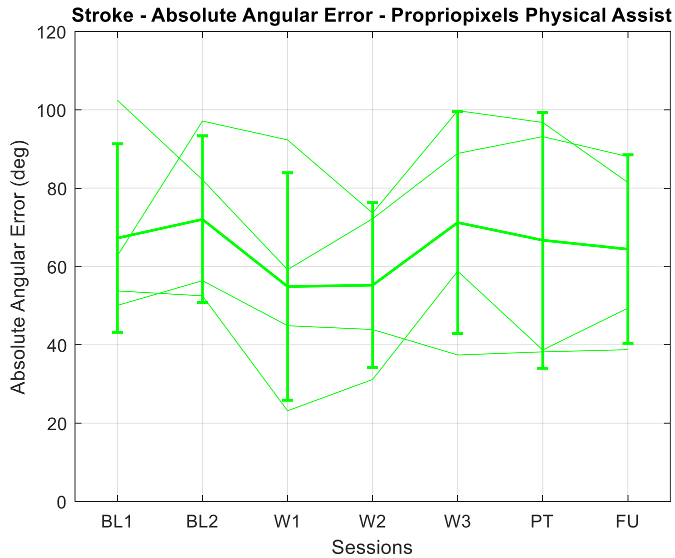



Figure 30: Absolute angular error along training for Group 3 - Proprioception with Physical Assist.

There is no significant improvement in any of the groups, however there are not enough participants in each group yet (group 1 has n=6 subjects, group 2 has n=7 and group 3 has n=4) to make any assumptions about the effect of training in the different game modes.

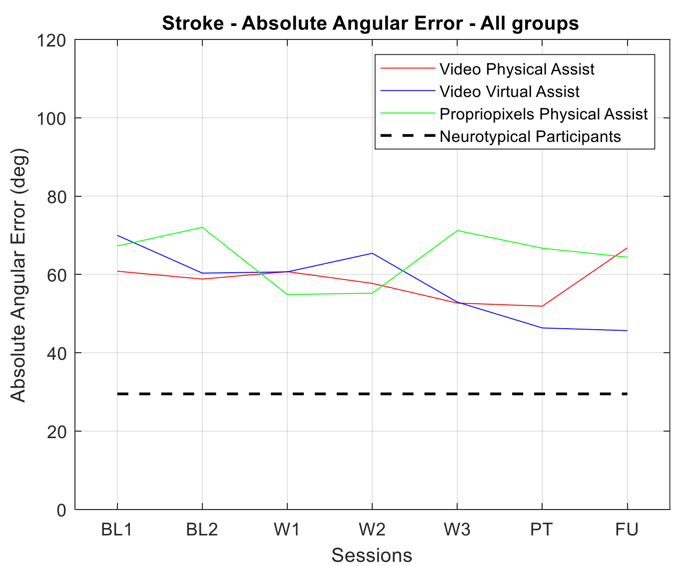



Figure 31: Absolute angular error along training for all groups

## 4.2 Learning Through a Game

Another aspect to analyze is if patients improved along the duration of a single game. Figure 32 shows that there was no learning through the course of the 20 jumps that they must do in a single game.

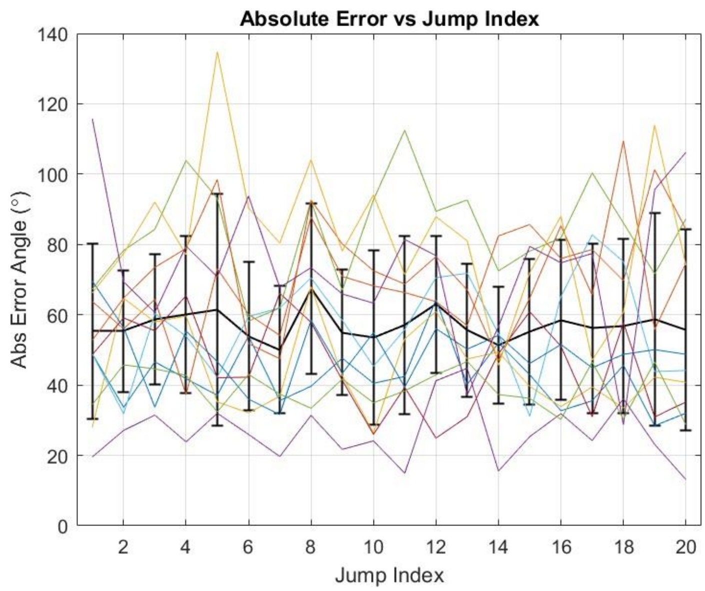



Figure 32: Absolute angular error along each jump index in a game.

# 5. DISCUSSION

To summarize, we developed a novel robotic assessment for thumb proprioception called Circle Jump. We then conducted two experiments to validate it, one involving neurotypical participants and the other stroke survivors. The unimpaired subjects underwent the Circle Jump assessment six times within a single session, incorporating variations in speed, direction, workspace size, and finger (thumb or index). For the stroke patients, the same Circle Jump assessment was performed across seven sessions over a two-month training period to assess potential improvements over time.

Our findings from the neurotypical experiment revealed a significant dependence on the direction of rotation, manifested as a large increase in error when rotation direction was switched following a period where participants experienced the opposite direction. To our knowledge, this is first-of-its-kind evidence of a new form of sensory adaptation. There was also a slight effect of speed and the finger used among neurotypical participants. Specifically, there was also a small but statistically significant reduction in error when the thumb rotated faster and when the index finger was employed.

In the case of stroke survivors, mean thumb proprioception errors were approximately double those for the neurotypical population. Errors remained stable across the seven assessment sessions, showing only a small, nonsignificant improvement over this time.

We now discuss these results, including proposing a novel model of proprioceptive learning, followed by a discussion of limitations and future directions.

## 5.1 Directional Effects of the Neurotypical Study

An open question is whether proprioceptive learning shares resemblances with motor learning, particularly in terms of generalization. Generalization in motor learning denotes the capacity to apply acquired knowledge from one context to other contexts. When this generalization proves advantageous, it is termed transfer, while its detrimental impact is referred to as interference [39]. Research in motor learning regularly finds both generalization and interference [39]. However, research in proprioception learning has found only generalization and not interference. Specifically, previous research has consistently shown that various proprioceptive training techniques result in improvements (or no decline, but never deterioration) in proprioception, indicating evidence of positive transfer i.e. generalization [10]. However, for proprioceptive learning to align with motor learning, there should also be indications of interference. This would manifest as a decline in certain aspects of proprioception due to training in a different aspect. We propose that this phenomenon is evident in the data from the Circle Jump game.

When examining the impact of altering the rotation direction, the derived plots (see Figure 20, Figure 21 and Figure 22) bear a resemblance to those depicted in studies addressing motor adaptation to dynamic environments [40], [41]. In these studies, participants engaged in reaching movements under externally applied forces within a mechanical environment. Over time, hand trajectories within the force field converged toward a path closely resembling that observed in unrestricted space. Subsequently, the abrupt removal of the force field post-training led to the analysis of resulting reaching paths, termed aftereffects. These trajectories were essentially mirror images of those witnessed during the participants' initial exposure to the field. This implies that the motor controller gradually constructed a model of the force field—a model used by the nervous system for predicting and compensating for external forces [40].

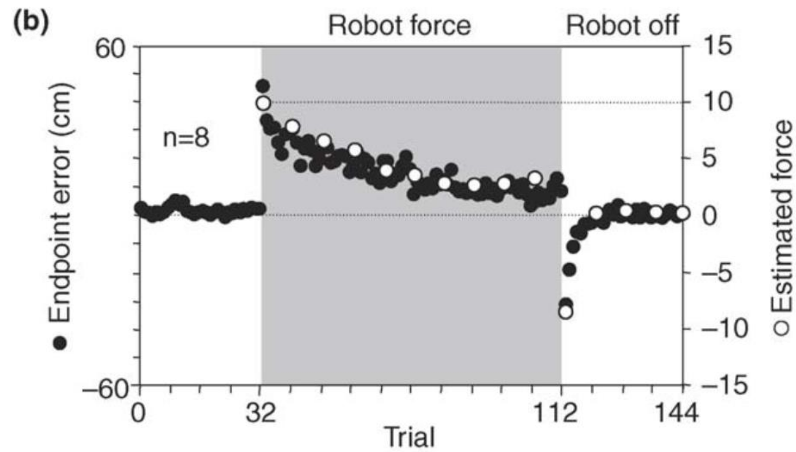



Figure 33: Effect of adding a robotic force field to a reaching task and aftereffect of removing that force field after training. Extracted from [41].

In the Circle Jump task, prolonged training in the primary direction was followed by a significant increase in the signed angular error upon altering the rotation direction. This pattern closely mirrors the change observed when the force field was initially activated, as illustrated in Figure 33. Upon restoring the rotation direction to its original state, the error diminished, reaching levels even lower than those recorded before the change in directions. This phenomenon aligns with the reported mirroring aftereffect observed in motor learning models.

## 5.2 Proprioception Learning Model Hypothesis

This suggests that the brain is creating a proprioceptive map and adjusting it based on what the thumb is experiencing. From a robotics perspective, this mapping should not depend on rotation direction. The process would be something like:

- The participant sees a target angle on the screen $\theta_{Screen_{Target}}$.
- They transform that angle on the screen to an angle in their thumb space using

a mapping like $\theta_{Thumb_{Target}} = f\left(\theta_{Screen_{Target}}\right)$.

- For a robot, $f$ is a static mapping and velocity does not come into play.

In this case, the brain is using the velocity $\dot{\theta}_{Thumb_{Perceived}}$ somehow in that transformation. We propose the following proprioceptive learning model with the purpose of trying to explain this phenomenon.

- At the start of the training, the speed perceived by the subjects (green dashed line) is different than the actual speed of the thumb (black line); thus, there is a perceptual bias or error.
- After training in the main direction $\dot{\theta}_{Main}$ and receiving feedback, the brain adjusts the model to reduce that error, and that happens by increasing the offset of this straight line from $c_1$ to $c_2$.
- After changing the direction of rotation to $\dot{\theta}_{Opposite}$, the error becomes even bigger. After some trials, the brain starts adjusting again to try to reduce the error, by decreasing $c_2$ to $c_3$.
- This will cause the observed adaptation phenomenon, such that when the direction of rotation is changed back to the original one $\dot{\theta}_{Main}$, the error will be bigger than it was before changing directions.

This implies that the brain is constructing a proprioceptive map and refining it based on the thumb's experiences. In this scenario, the brain somehow incorporates the experiences of velocity, $\dot{\theta}_{Thumb_{Perceived}}$, into this transformation. The proposed hypothesis of the proprioceptive learning model is one possible explanation of the observed motor learning phenomenon.

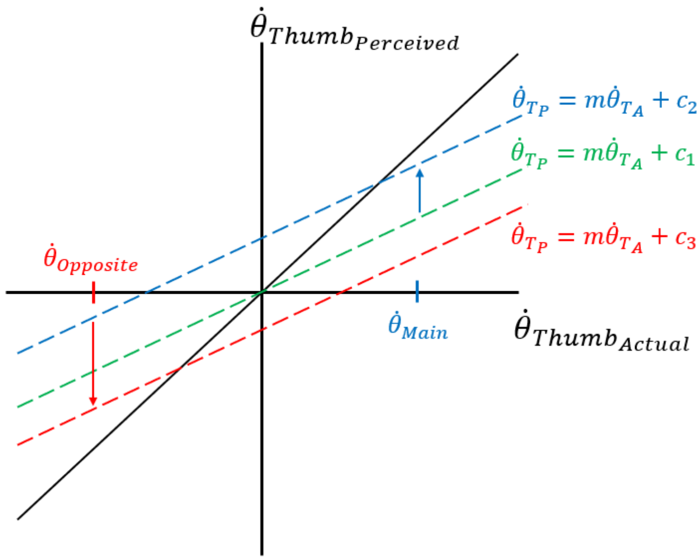



Figure 34: Proposed proprioceptive learning model. At the start of training, the speed perceived by the subjects (green dashed line) differs from the actual thumb speed (**black** line), indicating a certain bias or error. After training in the main direction $\dot{\theta}_{Main}$ and receiving feedback, the brain adjusts the model to diminish this error, illustrated by increasing the offset from $c_1$ to $c_2$ (blue dashed line). Upon changing the rotation direction to $\dot{\theta}_{Opposite}$, the error amplifies. After several trials, the brain adapts again to minimize the error, reducing the offset from $c_2$ to $c_3$ (red dashed line). Consequently, when the speed reverts to the original $\dot{\theta}_{Main}$, the error surpasses the pre-direction change level and the brain must readjust.

## 5.3 Effect of Finger Employed in the Neurotypical Study

It could be seen in Figure 24a that there was a significant reduction in the absolute angular error when using the index finger compared to using the thumb. We briefly suggest one possible reason. The thumb cuff of the FINGER robot is specifically designed to the anatomy of the thumb, and some participants reported that they could feel how the robot was pulling their index finger when it was going down and pushing on it when it was going up. That extra skin sensation might have allowed individuals to better estimate finger compared to thumb orientation.

## 5.4 Quantifying Thumb Proprioception in Persons with a Stroke using Circle Jump

In the case of stroke survivors, we found using Circle Jump that mean thumb proprioception errors were approximately double those for the neurotypical population. This is consistent with a large body of research noting that stroke commonly impairs proprioception [42], [43], but presents a novel quantification of the magnitude of thumb proprioceptive error after stroke. Despite having the participants engage in 3 weeks of robotic finger movement training that challenged proprioception, errors remained stable across the seven assessment sessions, showing only a small, nonsignificant improvement over this time. This was surprising to us as systematic reviews have found that a variety of training techniques can routinely be used to improve proprioception [10]. This could be attributed to the emphasis of therapy sessions for stroke survivors on the extension and flexion of the index and middle fingers, with relatively less attention given to the thumb, amounting to only 40 repetitions per week.

## 5.5 Limitations

The neurotypical study has a few limitations concerning the order in which the tasks were presented to the participants. The task order for participants was pseudorandomized. Initially, the order for the first participant was randomized, and for subsequent participants, the first task was moved to the last position. For example, if the first subject performed the tasks in the order 5 – 1 – 4 – 2 – 3 – 6, the second subject did them in the order 1 – 4 – 2 – 3 – 6 – 5, and the third one did them in the order 4 – 2 – 3 – 6 – 5 – 1.

On the one hand, this randomization method was chosen without anticipating the aftereffect when changing directions, which affected the task right after the opposite direction task by increasing its absolute error. The primary issue with this method is that task number 2 (medium speed) follows task number 4 (opposite direction) for most participants, making it susceptible to the aftereffects of switching directions. Moreover, task number 2 serves as the baseline for comparing various parameters (speed, direction, workspace size, and finger used), introducing potential contamination in those comparisons due to aftereffects.

On the other hand, the aforementioned randomization method was used for the initial 15 participants. However, upon analyzing the data and observing directional effects, a decision was made to relocate the opposite direction task to the end of the list for the last 11 participants. While maintaining the previously randomized order, task number 4 was consistently moved to the last position. This adjustment aimed to better observe the effects of changing direction after five consecutive games in the same direction. Unfortunately, this modification did not consider the aftereffects when returning to the main direction for the last 11 participants, so the data for this aspect is unavailable.

The primary constraint in the stroke study currently resides in the limited number of participants in each group, preventing the acquisition of statistically significant results at this stage.

## 5.6 Future Work

Participants in the neurotypical study also engaged in proprioceptive tasks involving their index and middle fingers, as well as their ankles, to facilitate a comparison of proprioception in the distal parts of the limbs. Moreover, ongoing data collection involving older neurotypical subjects aims to assess the impact of age on thumb proprioception.

In the stroke study, additional data collection is underway, and it is anticipated that once completed, it will yield further insights into thumb proprioception learning following a neurological injury such as a stroke.

Additionally, a forthcoming study is set to address the previously outlined limitations in the neurotypical participants. This study will specifically focus on speed and direction dependence, with the task order structured as follows: 3 Main direction games at Slow, Medium, and Fast speeds (in a truly random order), followed by 1 Main direction game at Medium speed, 2 Opposite direction games at Medium speed, and concluding with 2 Main direction games at Medium speed again (task numbers: random(1 – 2 – 3) – 2 – 4 – 4 – 2 – 2). This design ensures a clear comparison of speed effects among the first three tasks and provides a thorough examination of the effects and aftereffects of changing directions consistently at the same speed.

# 6. CONCLUSIONS

This thesis aimed to introduce an innovative robotic tool for assessing thumb proprioception, named Circle Jump, and to evaluate its effectiveness in assessing thumb proprioception in both neurotypical individuals and stroke patients. The Circle Jump game required participants to use the sensed position of their thumb, rotating in a circular motion, to determine when to trigger a jump from one circle to another.

In the neurotypical study, a comprehensive analysis of jump errors was conducted, focusing on variations in speed, rotation direction, workspace size, and the finger used, including an analysis of angular dependence. Results revealed a significant difference in angular error after changing the direction of thumb rotation, resembling a pattern seen in motor adaptation under a force field. Thus, using the Circle Jump assessment, we believe uncovered a novel form of sensory adaptation.

In the stroke study, the Circle Jump game served as a tool to assess the baseline level of thumb proprioceptive impairment that stroke causes, as well as any improvement of thumb proprioception throughout a three-week therapy intervention, enabling a comparison between baseline and post-therapy levels, and even checking for retention at a one-month follow-up visit. Findings indicated some improvement in proprioception, although not reaching statistical significance potentially due to the small sample size. Additionally, a comparison between different therapy techniques was performed, but limited significance was observed due to the small size of each group.

In summary, the study illustrated the efficacy of the Circle Jump game in evaluating proprioception in both neurotypical individuals and stroke patients.

These findings hold significance for the development of new assessment tools and interventions designed for individuals dealing with proprioceptive impairments.

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