A Home-based hand rehabilitation platform for hemiplegic patients after stroke: a feasibility study

By

Jasem Banihani

A thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

In partial fulfilment of the requirements of the degree of

MASTER OF SCIENCE

The College of Rehabilitation Sciences
Rady Faculty of Health Sciences
University of Manitoba
Winnipeg, Manitoba

Acknowledgment

There's a saying: "*Gratitude makes sense of our past, brings peace for today, and creates a vision for tomorrow*" As I ponder my academic journey, a flood of emotions and memories come to mind. The peaks of joy and valleys of despair, where at moments I felt on the brink, questioning my path.

At the forefront of my gratitude are my parents. Their unwavering love and support, even from thousands of miles away, have been my constant. My father, through his unparalleled work ethic, exemplified the virtues of discipline and perseverance. He's left me often wondering about the intensity of his dedication. Now, it's clear; he was sculpting a lesson of resilience for me. My mother, with her innate grace in facing adversity, became my touchstone, reminding me that with calm and patience, even the most daunting challenges can be overcome.

Dr. Amine Choukou's guidance was invaluable. When I felt submerged by research and doubts, it was his sage advice that steered me back. His unwavering support acted as the anchor of my academic pursuits.

A special acknowledgment goes to my committee. Your insights and prompt feedback have been transformative, shaping not only my thesis but also my approach to research. Lastly, I offer my sincere thanks to the devoted staff of the University of Manitoba. Each step of this journey, from minor details to significant milestones, was navigated smoothly because of your assistance. My heartfelt appreciation extends to each of you for being an integral part of this endeavour.

Table of contents

List of Figures

List of Tables

Terminology

1. Tele-rehabilitation: Telerehabilitation delivers medical or rehabilitative treatment to individuals with rehabilitation needs via telecommunication or the internet.
2. iManus: The iManus platform is an innovative, mobile, and user-friendly platform, utilizing a sensorized smart glove for telerehabilitation purposes. Designed for physiotherapists and occupational therapists, it provides a comprehensive collection of supervised rehabilitation exercises. With iManus, professionals can remotely monitor and treat patients, specifically those facing acute or chronic distal upper limb limitations resulting from neurological diseases. By providing remote access to therapy, consistent use of the iManus can promote active engagement of the hand, which could serve as a preventative measure against complications arising from disuse.
3. Hemiplegia: Hemiplegia is a symptom characterized by one-sided paralysis. Hemiplegia can occur on either the right or left side of the body. It appears because of brain or spinal cord injuries or diseases. Hemiplegia can be temporary or permanent, depending on the reason.
4. Synchronous: therapy sessions being conducted simultaneously under therapist supervision.
5. Asynchronous: the patient does the therapy sessions without direct supervision by a therapist.
6. Tactile Robotics, a company based in Winnipeg, built the iManus telerehabilitation platform in collaboration – and shares the intellectual property of this innovation – with Dr. Amine Choukou, Associate Professor at the University of Manitoba's College of Rehabilitation Sciences. The iManus technology has been disclosed in *Maddahi, A.; Choukou, M.-A.; Nassiri, A.M.; Maddahi, Y. A remote training and practicing apparatus and system for upper-limb rehabilitation. United States Patent, US 63/178,735, 2021.*

Keywords

Telerehabilitation, e-Health, at-home hand rehabilitation, remote physical therapy, telemonitoring, non-supervised therapy, hand exoskeleton.

Abstract

Background: Patients with stroke often experience weakened upper limbs, making daily tasks difficult. Although rehabilitation devices are available, patients often relapse after discharge due to insufficient practice. We present a home-based hand telerehabilitation intervention using the iManus platform comprising a sensorized glove that captures hand movement range of motion values and a mobile app for the patients, alongside a therapist portal for monitoring patient progress.

Objective: This research aimed to examine the feasibility, safety, and effectiveness of a home-based telerehabilitation intervention, in improving hand function for individuals with mild stroke. Additionally, a qualitative approach was used to explore users' experiences, perceived benefits, and challenges associated with using the platform in a home setting.

Methods: In this single-case study, we delivered a hand telerehabilitation intervention to a chronic stroke patient with impaired hand function using the iManus platform. The intervention consisted of 40 home sessions over eight weeks. We assessed feasibility through user adherence and feedback obtained using a System Usability Scale (SUS) and a semi-structured interview with the participant and an informal caregiver. Safety was evaluated by monitoring pain levels using the Visual Analog Scale (VAS), while efficacy was determined through observing the changes in range of motion using the iManus platform and clinical outcomes measures, namely the Fugl-Meyer Assessment (FMA) and Jebsen Taylor Hand Function Test (JTHFT).

Results: The participant completed all 40 assigned sessions, with each averaging 20 minutes. Usability scored 77.5 out of 100 on the SUS. User feedback from the interviews revealed improved mobility and control over therapy as benefits, while also indicating room for improvement in the intervention's adaptability and functionality. During the intervention, the participant noted no pain increase, and the telerehabilitation platform recorded range of motion improvements for all finger and wrist joints, excluding wrist extension. The FMA scores were 43 at T0, 53 at T1, and 56 at T2, while the JTHFT scores were 223 at T0, 188 at T1, and 240 at T2.

Conclusion: This single case study demonstrated the feasibility, safety, and efficacy of a home-based hand intervention for stroke survivors. The participant demonstrated improved hand functions, adherence to the program, and reported satisfaction with the intervention. However, these results are preliminary and require further validation in a larger scale study.

I. Introduction

According to the World Health Organization (WHO), stroke is the third most significant cause of mortality in developed nations, with roughly 15 million stroke occurrences [1]. One-third of stroke victims die, and another one-third suffer lifelong impairment due to the incident [2]. Stroke can cause a wide variety of functional deficits, including language, cognition, sensory, and motor capabilities, depending on the site of the brain damage [3]. After a stroke, a patient's ability to execute daily tasks is impacted by motor impairment. For most patients, recovery of upper-limb motor function is slower than the recovery of lower-limb motor function [2]. In addition, the upper limb is required for most everyday tasks, stressing the need for good upper limb rehabilitation.

A series of rehabilitation techniques have been developed and refined in recent decades to improve the effectiveness of upper limb rehabilitation among stroke patients [4]. These techniques include task-oriented motor training and constraint-induced movement therapy. Each of these treatments has a lot of theoretical advocates, and each has clinically been proven to be successful; for example, CIMT improves mobility on the affected side, according to several studies [5,1]. In their everyday lives, CIMT participants reported "significant to very significant" improvements in the functional use of their affected arm; gains in upper extremity function have been documented after constraint-induced treatment at all stages after the onset of stroke [6]. However, sixty percent of stroke patients still have difficulty utilizing their damaged upper limbs after completing a course of standard therapy [7]. As a result, developing innovative rehabilitation procedures capable of assisting patients in reaching a better level of recovery has become critical.

The Canadian Best Practice Recommendations encourage individuals to be challenged to learn the necessary motor skills by performing novel activities repeatedly and intensely [8]. Active and passive upper limb motions seem to aid recovery by influencing somatosensory input, motor planning, soft tissue characteristics, and spasticity [9, 10, 11]. However, because these comprehensive techniques typically need a therapist to work individually with patients, they are often slow, lengthy, and expensive. Due to a lack of resources, rehabilitation treatment may be insufficient in duration and intensity, resulting in poor functional return [12]. Furthermore, with the incidence of stroke expected to rise significantly over the next 20 years [8], so will the demand for therapy.

Technology offers solutions to challenges in upper limb rehabilitation, addressing limited resources and ensuring access to care in underserved communities [13]. Remote rehabilitation through telerehabilitation systems enables stroke patients to continue their recovery at home, eliminating the need for frequent visits to outpatient clinics. Consequently, there's a push towards cost-effective smart platforms with diverse programming to enhance practice opportunities.

Innovations in telerehabilitation have led to the development of home-based rehabilitation services. This approach not only allows patients to train in a familiar environment but also promotes active, concentrated training with continuous access to a range of tools. Devices like hand telerehabilitation systems, which provide performance feedback, increasing the effectiveness and adherence to these treatments [14]. Moreover, telerehabilitation platforms offer therapists remote patient monitoring capabilities, potentially easing the burden on healthcare systems facing challenges from an aging demographic and the rise of chronic conditions such as stroke [13]. Advancements in rehabilitation robotics could present opportunities for intensive, safe training for those with motor impairments post-neurological injuries. These devices focus on high-intensity, repetitive, and interactive training, bringing about precise therapy quantification and patient progress tracking [15, 16]. The future holds promise for the integration of these telerehabilitation technologies [17], enabling self-directed training without constant therapist oversight.

1. Rationale for the study

It is critical to recognize that the recovery of function in the upper limbs, particularly the hand, in patients who have suffered a stroke is complicated and necessitates an active effort. To limit the decline of autonomy acquired with in-hospital rehabilitation, treatment should begin as early as possible, continue throughout time, and be carried out regularly for the patient [18, 19]. If the gains obtained during rigorous rehabilitation treatment in a hospital environment are not sustained by frequent daily exercise applying the activities learnt, they tend to regress at home [20, 21, 22]. At-home robotic devices could be beneficial if deemed easy, safe, and economically appropriate.

However, a common issue with those technologies is that they are complex to use and expensive [23, 24]. Most devices are designed for in-hospital use with professional supervision and are too complicated for patients to operate independently at home. Due to the decline of autonomy in patients who have a stroke and technologies being complex to use it has become critical to create a simple and effective novel telerehabilitation intervention capable of monitoring patients and assisting therapists to achieve the highest recovery possible. This research describes at-home hand rehabilitation intervention based on a novel portable platform: iManus [25], an innovative telerehabilitation platform consisting of a glove and two separate software applications for therapists and patients. iManus is intended to monitor and train individuals with upper extremity dysfunctions by providing a built-in flexible training program, visual feedback from the platform and real-time feedback from therapists. The software associated with the glove allows us to measure the range of motion (ROM) of the hand (wrist, fingers). iManus also provides therapists with the option of synchronous (therapist supervision) and asynchronous (no therapist supervision) therapy sessions, and both have specific benefits to the patient and therapist.

2. Purpose of the study

Purpose of this Study: This research aimed to examine the feasibility, safety, and effectiveness of a home-based telerehabilitation intervention, in improving hand function for individuals with mild stroke. Additionally, a qualitative approach was used to explore users' experiences, perceived benefits, and challenges associated with using the platform in a home setting.

3. Objectives of the study

1. Assess the feasibility of the hand telerehabilitation intervention by:
   - 1.1. Monitoring participant engagement and successful completion.
   - 1.2. Administering the System Usability Scale questionnaire to gauge the intervention's usability.
   - 1.3. Conducting semi-structured interviews with both the participant and caregiver to gather feedback on the intervention's process and impact.
2. Determine the safety of the intervention by using the Visual Analog Scale to monitor any changes in participants' pain levels during the intervention.
3. Evaluate the effectiveness of the telerehabilitation intervention in improving hand function by:
   - 3.1. Analyzing variations in Range of Motion (ROM).
   - 3.2. Employing standardized clinical tests, including the Fugl-Meyer Assessment (FMA) and Jebsen-Taylor Hand Function Test (JTHFT).

II. Background

Stroke patients often face significant challenges in regaining full functionality of their limbs, particularly their hands. Despite the numerous physiotherapy interventions available, many patients do not regain optimal hand use. Stroke patients without access to therapy are even more likely to underutilize their affected hands compared to those with access. Understanding the underlying reasons and potential solutions becomes imperative.

Over the past decade, there has been a substantial increase in the number of randomized controlled trials (RCTs) focusing on physiotherapy interventions for stroke. The research on "Stroke Interventions" has grown fourfold, with a significant 30 out of 53 interventions demonstrating strong evidence of positive effects on various outcomes. This growth indicates not only the rising number of interventions deemed as having 'strong evidence' but also the varied outcomes that these findings significantly impact.

In the realm of neurological rehabilitation, there's a diverse range of treatment techniques rooted in different philosophical backgrounds. While some techniques are backed by robust research, others lean more heavily on anecdotal evidence [26]. This discrepancy in evidence highlights the crucial need to identify the most effective interventions and fully grasp their nuances when applied in telerehabilitation. Given the profound impact on the quality of life when stroke patients do not use their affected hand and rely solely on one, it's imperative to ensure that telerehabilitation delivers the best possible therapeutic intervention for hand recovery.

Below is a brief overview of the definition of stroke and some of the physiotherapy evidence-based approaches used in stroke rehabilitation.

1. Stroke

According to the WHO, cerebrovascular attack, also known as acute stroke, is an attack on the brain with "rapidly developing clinical signs of focal or global disturbance to cerebral function, with symptoms lasting 24 hours or longer, or leading to death. There is no apparent cause other than the vascular origin, including cerebral infarction, intracerebral hemorrhage, and subarachnoid hemorrhage". Ischemic strokes account for 85% of all acute strokes. Hemorrhagic stroke accounts for about 15% of all strokes [27].

Ischemic stroke can be divided into three main types [27].

- Thrombotic blood clots emerge in a significant brain artery or small blood vessels deep inside the brain.
- Embolic - When a blood clot formed elsewhere in the body travels through the bloodstream to the brain and blocks blood flow.
- Systemic hypoperfusion - when the heart fails to deliver enough blood to the brain. There are multiple causes of systemic hypoperfusion, such as low blood pressure, loss of blood volume or heart failure.

A hemorrhagic stroke develops when a blood vessel supplies the brain bursts and bleeds. When an artery bleeds in the brain, the cells and tissues in the brain do not get oxygen or nutrients. As a result, pressure builds up in the surrounding tissues and irritation and swelling occur, leading to further brain damage. There are two types of hemorrhagic stroke [28].

- Subarachnoid hemorrhagic stroke is bleeding that happens in the space surrounding the brain (between the brain's surface and the arachnoid tissues that surrounds the brain).
- Intracerebral hemorrhagic stroke: Internal bleeding from a blood artery in the brain. The most common cause of intracerebral hemorrhagic stroke is high blood pressure.

2. Clinical presentation and patterns of stroke

After a cerebrovascular attack, performing ADLs is compromised with clear limitations in the hand and, elbow, shoulder [2] and suffering impaired arm function after stroke is one of the most detrimental consequences to social and work-related participation. In addition, movement and sensation impairment result from stroke damage to the sensory-motor cortex, subcortical areas or cerebellum. Damage to these areas can present the following symptoms:

- Loss of motor control makes spontaneous movement generation difficult or prevents fingers, hands, and arms coordination.
- Impairment in sensory and proprioception that affects awareness and position of the limb.

- Non-use of a limb after a stroke causes several changes in the skeletal and neurological systems, including [29]: Shortening of muscles (contracture) and weakening of muscles (paresis).
- Spasticity (abnormal increase in muscle tone or stiffness of muscle).
- Shoulder subluxation (partial or incomplete dislocation).
- Pain is usually the result of shoulder subluxation or changes in the musculoskeletal system.

Activities that require coordination with the upper limb and fine finger movements are notably harder for stroke patients [30]. Over time, the increased reliance on the unaffected limb, coupled with the neglect of the paretic limb, leads to learned non-use. Also, stroke can harm mood and cognitive capacity, limiting functional capabilities [29]. Subsequently, social engagement tends to decline due to the lack of meaningful activities.

3. Neuroplasticity

Neuroplasticity is the anatomical and functional changes in the brain that provide adaptability to learning, memory, the environment, and rehabilitation after brain trauma. It is a dynamic process that involves changes in the number of brain nuclei and structures, as well as multiple functions and interactions [31,32,33]. Although spontaneous remodeling changes occur following brain damage caused by stroke, these changes are insufficient to generate a noticeable functional recovery [34]. Rehabilitation can increase dynamic processes in the nervous system in healthy and injured brains to facilitate adaptation to new experiences [35, 36]. Based on neuroplasticity research, it is crucial to establish an effective rehabilitation and therapy technique for ischemic stroke-related brain damage. Through the stimulation of neuroplasticity, such as through increases in neuronal activity and the potentiation of postsynaptic excitation, as well as improvements in dendritic spine formation and axonal myelination following ischemic stroke [37], exercise is a beneficial and practical rehabilitation technique for increasing cognitive and motor functional recovery. Several human and animal studies [38, 39, 40, 41] have demonstrated that rehabilitation training after a stroke result in considerable functional recovery. In an exploratory trial on chronic stroke, physical training substantially impacted mobility. Some patients had apparent cognitive gains accompanied by brain activity changes that most likely represented neural plasticity [42].

The expression of neuroplasticity-relevant genes, such as protein kinase C (PKC), N-methyl-D-aspartate (NMDA) 2A receptor, the neurotrophic tyrosine kinase receptor 2 (NTRK 2), and microtubule-associated protein (MAP) 1b, was significantly altered in rats exposed to both forced arm use and voluntary exercise to improve functional recovery after photothrombotic stroke [43].

Microstimulation and functional mapping experiments have demonstrated that stroke recovery can result in surviving brain regions adopting the functional responsibilities of damaged brain structures [44]. For example, neuronal rearrangement in the peri-infarct cortex plays a role in the recovery of motor function following a stroke which is started by cellular responses to degeneration [45]. As neurons in the ischemic area die, their axons and synapses degrade extensively across brain regions, triggering regenerative responses that facilitate forming new connections between surviving neurons. This process's new connections have a vast range of possible patterns and benefits [46].

Behavioral events following a stroke stimulate neuronal reconfiguration by altering the activity of regenerated circuits. Skilled forelimb reaching training helps neurons send new connections to the denervated forelimb area in the spinal cord. These new connections help motor map reorganization and exercise-induced task-specific recovery in the secondary motor area [47]. The Mol Neurobiology reconfiguration of task-specific multiregional brains may be related to the use-dependent plasticity generated by recurrent motor training paired with brain stimulation. During trained extensor movements, brain activity is significantly reduced in certain regions, including the contralesionally premotor cortex, the contralesionally cingulate motor cortex, and the ipsilesional sensorimotor cortex, and this is associated with functional improvements in the affected hands [48]. The motor performance (efficacy, velocity, and success) of monkeys treated with subthreshold electrical stimulation and rehabilitative training may be enhanced for several months. Cortical mapping has shown the widespread formation of new hand representations in the peri-ischemic motor cortex [49].

Age may influence the functional reorganization induced by exercise after an ischemic stroke. After an ischemic stroke, the infarct volumes of older mice are more significant than young mice. Task-specific rehabilitative training may enhance motor function. Growth of the rostral forelimb region is observed in young mice, suggesting that rearrangement of the motor cortex may be constrained by brain damage or ageing [50].

Consequently, elderly survivors or patients with more severe brain injuries may benefit more from combination therapy than exercise training alone. Exercise-mediated post-stroke recovery can contribute to surviving brain regions assuming the functional responsibilities of injured brain parts by boosting axonal regeneration and activating new connections between surviving neurons. In addition, the remodeling of brain function is linked with the rise in the number of newborn neurons, dendritic arborization, and axonal development. The effects of exercise training may be accompanied by changes in axonal projections and the creation of new neural circuits from the same areas to other locations.

4. Task-Oriented Training

A task-oriented training is an activity-centered approach that involves repeated training of a task with a focus on functional performance toward the practical completion of the task, thereby increasing the exercise training effects through the environment, task analysis, feedback, and repeated training [51]. Functional tasks help organize motor behavior by putting the reflex loops back into a network of neural CNS patterns. On the other hand, occupational performance lets people interact with different environmental systems built around people and their environments. A patient's behavior is altered following a human or environmental system change. Based on this theory, as the patient tries to reach a functional goal, the approach works best when given a practical task instead of training in the typical movement pattern. This provides the patient with a chance to try to solve problems on their own.

In addition, the patient engages in a range of task-oriented activities as a result of effective therapy that incorporates various functional activities. In the task-oriented approach as a therapeutically valuable intervention for patients, the functional execution of tasks related to everyday living is more beneficial than the practice of tasks designed for a clinical context. Consequently, the therapy aims to improve motor capabilities when patients actively use the afflicted upper limb [52].

5. Rehabilitation robots

Several therapeutic robots for neurorehabilitation are undergoing clinical testing and development. Only devices for treatment of the upper extremities exceed 120 in number [23]. The various technical solutions vary according to actuators, sensors, and control strategies. The purpose of the devices is to facilitate movement during physical therapy. There are two primary groups of robots in terms of their mechanical structure: end-effector-based and exoskeleton-based robots. Both forms offer intensive, high-repetition treatment. However, they interact differently with the user. End-effectors are typically connected to the human arm at a single, distal position. The movement of the end-effector modifies the arm's position at this connecting point. It also indirectly adjusts the position of other limb segments (such as the upper arm) and generates interaction torques in each limb segment that are not entirely controlled by the device [53]. In stroke patients, movement may cause pathologic compensatory motions that might be harmful. Multiple end-effector devices integrated at specific limb segments are combined in modular systems to avoid this compensatory motion [54]. Exoskeletons are arm-encircling orthoses that resemble the skeleton. The device segments are aligned with the anatomical segments of the human arm at several attachment points. The device's rotating axes closely resemble the rotational axis of the human arm. Exoskeletons require more sophisticated control and compensating algorithms than end-effectors. However, they allow for more natural arm motions. Each segment of the arm's position may be accurately specified, and each joint can be controlled individually [54].

The benefits of robots extend beyond rigorous, high-repetition training in a motivating environment. Robots can enhance learning tactics that are not possible with conventional types of therapy. Error amplification is an example of a successful learning approach performed with robots. Error amplification is based on the notion of amplifying trajectory mistakes throughout a movement, often haptically by the robot or graphically via the display. This amplification may convey the inaccuracy to the performer's notice. The effectiveness of error amplification depends on the individual's skill level [55]. It aids in learning the spatial components of trajectories [56] and appears particularly useful for stroke patients with mild impairment. Beneficial for more seriously damaged people is not haptic amplification of an error but rather haptic guiding through a movement. As a form of "proprioceptive observation," this passive movement alone can teach movement and cause brain changes [57, 58].

In addition to offering novel therapy alternatives, robots may enhance understanding of motor control rehabilitation mechanisms and time course. Motor control deficits following a stroke are not fully patient-specific. Typical patterns of impairments (e.g., pathological synergies) are recognized across participants and are part of the rehabilitation process [59]. Sensor-equipped robots can expose these patterns in more detail and with better precision than clinical testing or motion-capture systems. The latter offer kinematic data (such as location, velocity, and acceleration) regarding a movement. Additionally, robots with haptic sensors may capture kinetic data, such as forces or torques [60].

An example is the duration of the recovery process. It is generally considered that the complete recovery of motor control, i.e., the ability to carry out a movement in a similar manner as before damage, occurs in the first 3–6 months following a stroke [61]. Developments beyond this sensitive time may be nearly fully mediated by compensation, learning alternate movement patterns that differ from those utilized before the injury (such as using the trunk for arm-reaching motions). The study of robot motions recently showed that real recovery (i.e., motor control) and compensatory movements are already separated in the early stages of stroke. After just five weeks of intervention, the real recovery of arm motor function appears to plateau [62]. Beyond this point, functional improvement is dominated by compensatory and strength gains. Applying machine learning and analyzing data collected during robotic treatment on large groups of patients will alter our knowledge of the elements that influence recovery after stroke. It may show how gender affects stroke recovery. This is significant since nothing is known about gender variations in long-term healing. There will be new ways to improve neurorehabilitation therapies. Individualized rehabilitation therapy will be administered based on the phase, documented deficiencies, and level of impairment. The objective is to enhance performance in both the early and late chronic phases.

6. COVID-19 and stroke telerehabilitation

The COVID-19 pandemic has accelerated the adoption of telehealth, particularly in the field of rehabilitation for stroke patients [63]. Given the necessity of maintaining health services and people's growing comfort with videoconferencing technologies, telehealth has become an essential tool. Telerehabilitation refers to the remote provision of rehabilitation services, from consultations and assessments to therapeutic programs, through various digital means, such as real-time videoconferencing or email-based communication [64]. In some research contexts, it has been supplemented by sensors, wearable devices, and interactive gaming strategies [65].

The pandemic's constraints have curtailed traditional access to rehabilitation services in hospitals and communities, highlighting the importance of telerehabilitation as an alternative to support care and prevent disease spread [68]. It allowed for the adaptation of existing face-to-face programs to remote delivery via modern technologies. While the majority of stroke patients who have used telerehabilitation services have expressed satisfaction, this area of healthcare is still evolving and must address various challenges, complexities, and compromises [66]. The transition from conventional to online or hybrid models must be handled with care, considering factors such as quality maintenance, inclusive access, and continuous data collection to assess various performance metrics. It is also necessary to reflect on telerehabilitation's financial, ecological, and societal impacts [66].

Evidence from studies like the 2020 Cochrane Review has shown that telerehabilitation's effectiveness is on par with traditional care, although some trials have raised questions about the quality of evidence [68]. Despite the potential of telerehabilitation to enhance therapy accessibility, the "digital divide" still presents risks of exclusion for certain population groups, including those from disadvantaged backgrounds, the elderly, and people with disabilities or connectivity issues [69, 70,71]. Nevertheless, telerehabilitation can facilitate treatment access in various global healthcare scenarios where physical travel may be burdensome or unfeasible [71]. This approach offers stroke patients more choices and control over their treatment, and it can connect them with skilled healthcare providers worldwide.

The perceived cost-effectiveness of telerehabilitation, attributed to reduced travel and transportation expenses, needs to be studied more rigorously [72]. While travel time may decrease, inefficiencies can arise due to missed appointments and technological glitches. Investment in equipment, software, and technical support, along with ongoing maintenance costs, must also be factored in [73]. Moreover, despite technological advancements, barriers remain in achieving a seamless telerehabilitation experience. Regulatory frameworks, policies, and reimbursement methods must continue to evolve, ensuring alignment across providers and data privacy [73]. Establishing reliable and consistent reimbursement strategies is vital for the long-term sustainability of telerehabilitation services, solidifying their place in the healthcare landscape.

III. Proposed technology to support at-home hand telerehabilitation

iManus is a novel hand telerehabilitation platform consisting of a glove for the patient to wear and two software applications for both the therapists and the patients [25]. iManus is intended to train and monitor individuals with upper extremity dysfunctions by providing a built-in flexible training program and visual and real-time feedback to encourage correct motion, active and repetitive, and task-specific exercise. The sensors built into the gloves will allow us to calculate the ROM changes of the participants hands throughout the intervention.

1. Hardware

The iManus hand rehabilitation platform, designed by Tactile Robotics Ltd in Canada, was devised through a partnership with academic professionals from the University of Manitoba. This innovative device was created to supervise rehabilitation exercises of the distal upper limb. The system comprises a sensorized smart glove that enables the remote monitoring of upper limb rehabilitation tasks, negating the need for in-person clinic visits. Available in three sizes, the glove is made from flexible plastic. The smart glove is embedded with flex sensors that keep track of the hand's ROM. They record movements of the MCP joint – its flexion and extension – as well as all the wrist joint movements, including flexion, extension, ulnar and radial deviation. Flex sensors were chosen for the iManus platform due to several reasons. First, they provide highly accurate measurements of finger joint angles. Second, their lightweight nature and ease of handling cause minimal interference with natural hand movement when incorporated into a wearable device. Lastly, they remove the necessity for extra mechanical components, thus simplifying the design and reducing potential failure points.

2. Range of motion

The iManus device is strategically equipped with sensors, precisely located under the metacarpophalangeal (MCP) joints and extended to the wrist joint, to meticulously detect the movements of the MCP and wrist joints. It identifies the bending and straightening actions at the MCP and wrist joints, thereby collecting essential data on hand flexion and extension movements, crucial for accurately monitoring the Range of Motion (ROM) in the hand. During operation, the sensors are sensitive to changes in finger position, capturing the nuanced changes in joint angles as individuals flex or extend during sessions. It then transforms these changes into analyzable data, providing invaluable insights into the hand position throughout any therapeutic activity that the therapist has recommended to the patient. To test the reliability of the iManus a preliminary statistical analysis was performed, revealing a constant upward trend in the iManus device's range of motion (ROM) readings as the participant executed various degrees of flexion, from minimal to maximal. This analysis utilized data obtained from a healthy hand serving as a control, where the participant performed a series of flexion movements. The device's capacity to consistently record ROM values was evaluated for each finger's metacarpophalangeal (MCP) joint and phase through 30 repetitions, confirming the reliability of the iManus device in accurately detecting and recording hand movements. Although this testing was conducted with a single healthy participant during the pretesting phase, before actual testing with a stroke patient, the results (Figure 1) substantiate the device's ability to reliably differentiate between minimal and maximal ROM movements, suggesting its potential utility as a tool for overseeing and directing rehabilitation exercises. However, it's necessary to note the iManus device's limitations. Its sensors may not fully encompass the ROM of the proximal interphalangeal and distal interphalangeal joints, located respectively in the middle and end sections of each finger. This exclusion results in a less comprehensive assessment of hand movements. Despite such limitations, the iManus device still affords valuable insights into hand ROM by focusing on MCP joint movements, facilitating the tracking of finger flexion and extension during various activities and rehabilitation exercises, and providing a foundational understanding of hand functionality in therapeutic contexts.

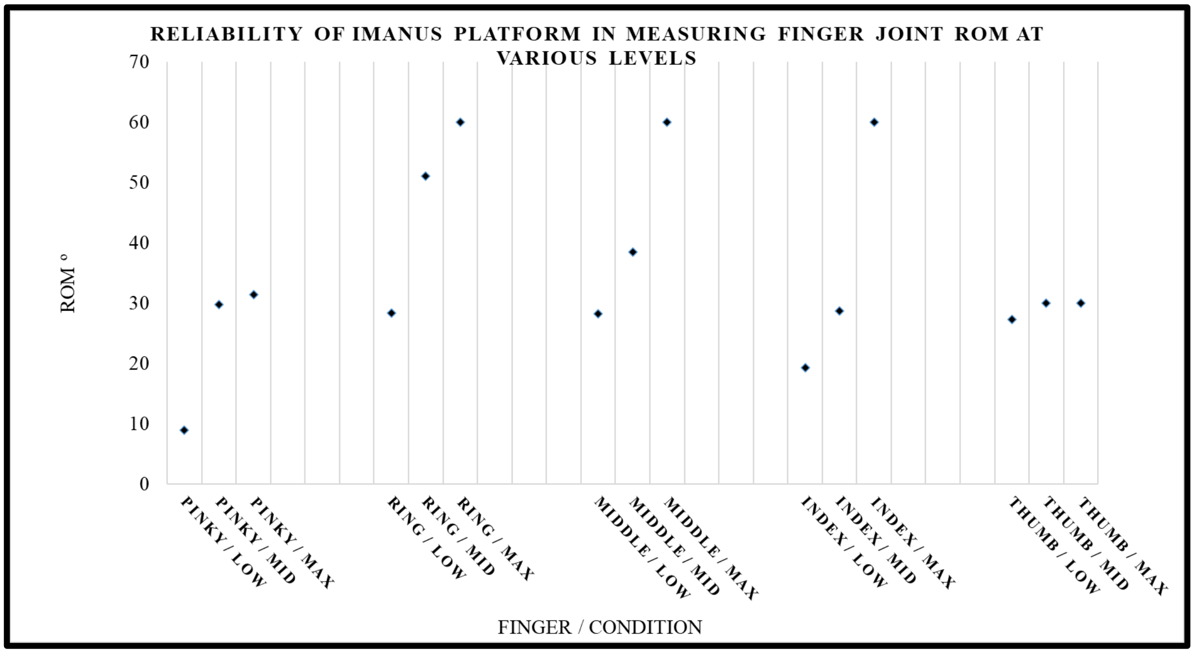

Figure 1 Results support that the hand telerehabilitation platform reliably records ROMº, suggesting its potential as a tool for monitoring and guiding rehabilitation exercises

3. Therapist interface

The therapist's interface is an integral feature of the hand telerehabilitation platform (HTP), facilitating effective communication between therapists and patients. This web portal offers various tools relevant to hand rehabilitation, including therapy assessment forms and diagnostic tools that allow therapists to maintain comprehensive records of patient conditions. Featuring distinct sections, the interface provides a space for therapists to view their list of patients and a calendar displaying individual session schedules. A standout feature of the HTP therapist interface is the ability to assign exercises directly to patients. This portal offers a library of 100 exercises focused on the distal upper extremity, encompassing stretches, strength training, and functional activities geared toward stimulating patient engagement and focus. In the event that the existing library of exercises does not align with a patient's unique needs, the interface provides the flexibility for therapists to augment additional exercises, enhancing customization and personalization (**Error! Reference source not found.**). This ensures that therapists have the freedom to tailor therapy exercises to the individual requirements of each patient.

Therapists can prescribe specific repetitions, sets, and rest times for each exercise (**Error! Reference source not found.**) Furthermore, the interface includes a 3D hand model that emulates the patient's distal upper extremity during the assigned exercises. As the therapist hovers the mouse over the model, the corresponding ROM for each finger is displayed. This feature allows the therapist to review the 3D model's video, comparing it with the patient's movements to ensure the exercises are performed correctly. Communication between therapists and patients within the iManus platform is versatile and tailored to fit varying needs and preferences. The platform offers therapists two distinct options for conducting therapy sessions, each with its unique features, to support effective hand telerehabilitation.

The first option is a synchronous mode, where therapists are present and actively supervise the patient during the therapy session. This mode utilizes a live webcam feature, allowing real-time observation, guidance, and interaction between therapists and patients. The immediate connection facilitates corrections, encouragement, and personalized feedback, creating an experience akin to in-person therapy but through a digital medium.

The second option caters to a more flexible approach through an asynchronous mode. In this setup, therapists do not have to be physically present during the therapy session. Instead, they can review a recorded video of the patient performing the exercises at a later time. This video is complemented by detailed data showing the range of motion values for the exercises performed by the patient. This asynchronous approach enables the therapist to analyze performance, adherence to prescribed exercises, and progress, even without real-time supervision. It also provides the patient with the autonomy to perform exercises at their convenience, while still ensuring that professional oversight and feedback are available. These two modes in the iManus platform provide a versatile and adaptable structure for hand telerehabilitation. Whether preferring real-time engagement or the flexibility of review and analysis after the session, therapists and patients can collaboratively choose the mode that best aligns with their professional judgment and the specific needs of each patient.

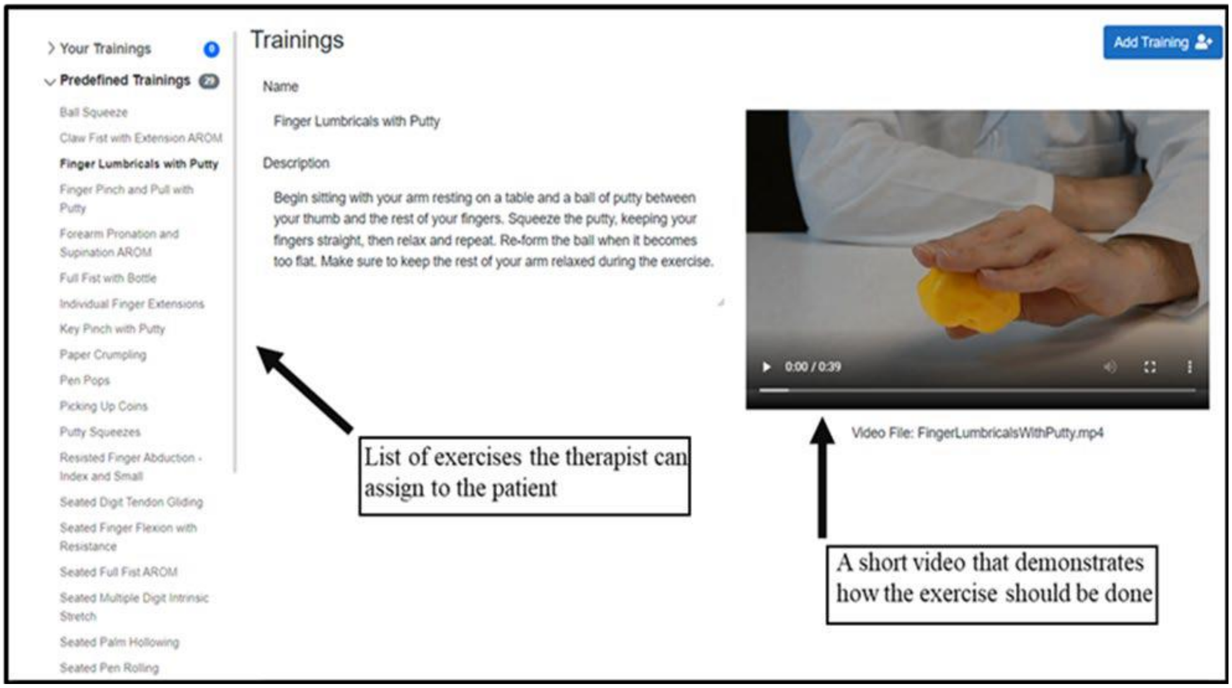

Figure 2 iManus library of exercises

Figure 3 iManus therapist interface for exercise modification in terms of number of sets and repetitions

4. User interface

The iManus patient application, available for download on both IOS and Android platforms, facilitates communication between the therapist and the patient. Patients are provided a unique code by their therapist to log into the application. Upon successful sign-in, the user interface displays a start button that can't be pressed until the application recognizes that the patient wore the smart glove. The application showcases videos of the assigned activities, detailing the number of repetitions, sets, and rest periods between sets. For each exercise, the patient is provided with four options: pause, discard the exercise, proceed to the next exercise, or end the session. This variety of choices affords patients a degree of autonomy, allowing them to take a pause if they feel fatigued. Feedback is generated on the success of the action, as well as the quality of each repetition's execution. In instances of discomfort or pain during an exercise, the patient has the option to discard the exercise and communicate their concerns to the therapist via the in-app chat box (Figure 4), or through the webcam, if the therapist is present. A significant design aspect of the system is its simplicity and ease of use, reducing the necessity for extensive training for health practitioners and patients.

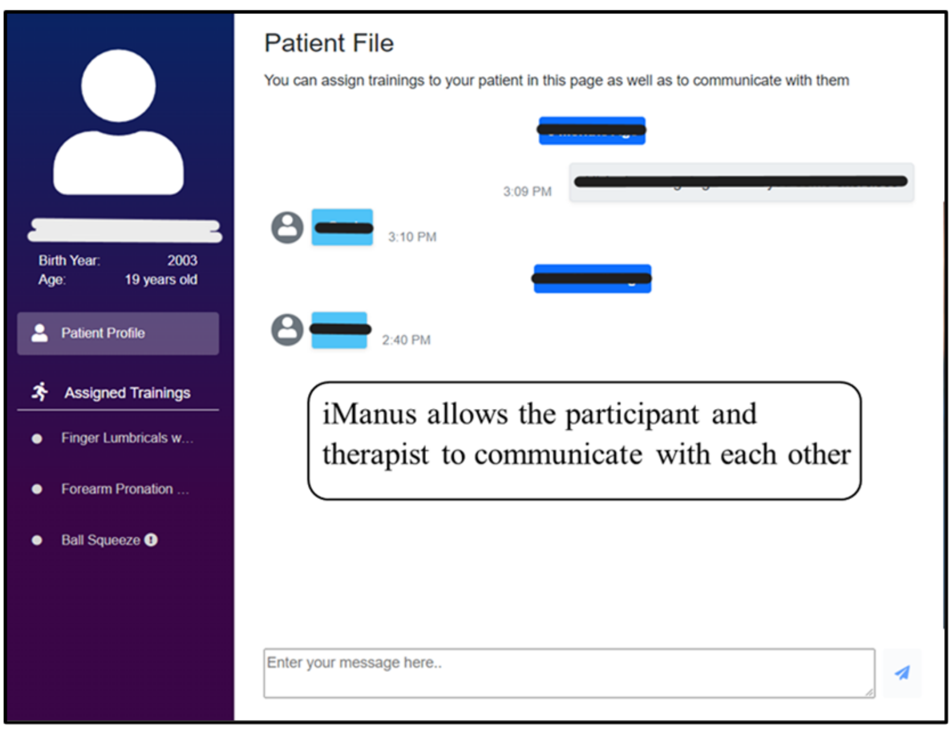

Figure 4 Chat box feature connecting the patient with the therapist

IV. Methods

1. The Participant

The present study included a female participant with a mild case of chronic stroke who utilized the iManus platform as a telerehabilitation tool at home for eight weeks. The choice of a chronic stroke patient over an acute one was guided by the stabilized neuroplasticity, safety considerations, and a consistent baseline functional level in chronic cases, which facilitated a clearer evaluation of the iManus platform [30]. Recruitment for the study was conducted through a convenience sampling method from a previous study in which I actively participated. The previous study focused on the rehabilitation of stroke survivors using a virtual reality device. The participant met the inclusion and exclusion criteria:

1.1 Inclusion criteria

- Age over 18 and 80.
- Patient in the chronic phase of stroke (more than six months after the onset of acute injury).
- Hemiplegic upper extremity dysfunction secondary to a unilateral ischemic or hemorrhagic brain lesion.
- Arm spasticity > 2 in the Modified Ashworth Scale [74].
- Able to flex the shoulder and extend the elbow.
- Subject with impaired hand opening but capable of partial movements.
- Absence of severe cognitive impairment as defined by Mini-Mental State Examination > 23 [75]. Able to follow instructions as prescribed by Mississippi Aphasia Screening Test ≥ 45.16 [76].
- Also, the participant must have the ability to give their consent, understand the platforms instructions, and perform the exercises.

1.2 Exclusion criteria

- If the participant has any contraindications to intensive hand training
- Upper limb pain
- Bilateral paresis
- Poor skin condition over the hand
- Individuals who have visual or hearing impairment do not allow the possibility to interact with the hand training platform.

2. Initial Assessment

The therapist and patient initially met at the participant's home for an assessment of the hand condition. A comprehensive hand evaluation was conducted to determine the participant's functional status, which led to a personalized treatment plan. Following this, an educational session took place where both the patient and caregiver were instructed on how to use the platform correctly. The topics covered included turning the platform on and off, troubleshooting in the event of malfunctions, donning and doffing the smart glove, and charging it as necessary. It is important to note that involvement from informal caregivers played a crucial role throughout all stages of education. Furthermore, before concluding the session with the therapist, a brief practice session occurred to ensure that both caregiver and participant were proficient in operating iManus effectively.

3. Intervention

In this feasibility study, we designed and implemented a treatment plan that was both personalized and adaptive to the participant's unique needs and preferences. This plan was proposed to a participant suffering from chronic stroke and spanned a duration of two months. The intervention involved telerehabilitation sessions conducted five times a week, with each session recommended to be 30 minutes long (Table 1). Additionally, for each session, participants were assigned five exercises to aid in their rehabilitation process. Our methodology for selecting exercises adhered to standard practices in stroke rehabilitation, with an emphasis on the reacquisition of functional skills and meaningful movements [77]. Specifically, the approach was rooted in task-oriented arm training, a strategy backed by significant evidence for improving post-stroke hand performance [78, 79]. The chosen exercises were designed to cover a comprehensive range of movements. In our approach, we prioritized participant autonomy and engagement by involving them actively in the exercise selection process. The participant also had a significant role in deciding their exercise schedule. This collaborative method was aimed at fostering a sense of autonomy and promoting adherence, potentially leading to enhanced outcomes. To further facilitate this, the participant was offered a choice between synchronous and asynchronous training sessions via the iManus platform. To ensure a transparent process, we shared in-depth information about each exercise, including the number of repetitions, sets, and rest intervals.

The participant opted for asynchronous sessions, offering them the flexibility to manage their rehabilitation schedule. The treatment plan was designed to be dynamic, with adjustments made based on several factors. These included participant feedback, therapist observations from recorded outcome measures, and ROM values derived from the device. The therapist conducted intentional and systematic adjustments to the training program by utilizing remote access to the therapist portal specifically designed for therapist utilization. The therapist would regularly access this portal on a daily basis in order to carefully examine potential messages received from the participant. Additionally, the therapist would use the interface to remotely monitor the participant advancement, adherence to the training program, and the duration of their training sessions. During the course of these monitoring activities, it was not necessary for the participant to be simultaneously present online. The therapist conducted a retrospective evaluation of session results, assuring diligent monitoring of the participant's advancement. Nevertheless, it is important to acknowledge that this specific approach did not attempt to include external motivational incentives in order to enhance the participant's adherence to the intervention. Outcome measures including the Fugl Meyer upper extremity scale, Jebsen-Taylor Hand Function test and the Visual Analog Scale were recorded three times during the study - before, in the middle, and after the intervention. The System Usability Scale and the semi-structured interview were conducted after the study had ended. To facilitate communication and address any concerns or technical issues, the participant was provided access to a technical help desk and an in-app chat to contact the therapist. Moreover, the therapist made weekly calls to check on the participant's safety and address any emerging issues. This study provides critical insights into the acceptability and practicality of using this intervention in real-world settings. This study shows how the intervention can adjust to suit various lifestyles and commitments. However, it also points out some challenges. These include the need for the participant to stay motivated during asynchronous training and the delay in receiving feedback from the therapist.

Table 1 Recommended intervention plan

Number of sessions	Number of exercises	Session duration
40	5	30 minutes ~

4. Data collection

Patients' data, including the ROM taken during the session and chat logs between the therapist and the participant were all uploaded to a secure server for the therapist to check and analyze at any time on the therapist's portal. Further, any technical issues encountered during the use of the iManus platform, and the solutions implemented to resolve these problems were documented for future reference and improvements. As part of the final evaluation, individual semi-structured interviews were conducted with the patient and the caregiver to explore their experience with the telerehabilitation service provided. All interviews were completed using a semi-structured interview guide, including open and closed questions (Table 2).

Outcome measures

4.1 Feasibility

4.1.1. Program completion data

That included the number of sessions the participant performed and the average time in minutes the participant spent exercising for each session.

4.1.2. The System Usability Scale

The System Usability Scale (SUS) offers a "quick and dirty" but trustworthy method for testing usability. It comprises a 10-item questionnaire with five possible responses, strongly agree to disagree, given to respondents Strongly. It enables the researchers to assess a wide range of goods and services, including hardware, software, mobile devices, websites, and applications. John Brooke originally designed it in 1986. The advantages of a SUS have been cited in more than 1300 journals and publications, making it an industry standard. In addition, the use of SUS has numerous advantages, including that it is a relatively straightforward scale when giving participants dependable outcomes; even with a small sample size, it is reliable because it can distinguish between useable systems and those that are not [80].

4.1.3. Semi-structed interviews.

To comprehensively understand the participant's experience with the telerehabilitation program, two semi-structured interviews were conducted post-intervention with the patient and their caregiver [81]. Employing an interview guide (Table 2), informed by the User Experience and Acceptance Models [82, 83], ensured pivotal topics were addressed. This format allowed for a thorough exploration of specific topics while adhering to the broader research objectives. Our primary analysis followed an inductive approach [84], embracing the study's exploratory nature. This approach highlighted emergence of themes and patterns directly from the data, rather than testing predefined hypotheses as in a deductive approach. The analysis process of the interview data was systematic and multi-staged. It began with the transcription of the recorded conversations, followed by coding the data to identify significant concepts. These codes were then grouped into themes, which were interpreted to extract meaningful insights. Techniques such as data reduction and summarization were employed to condense the findings, highlighting key patterns and their implications. To ensure the credibility and objectivity of the analysis, several measures were taken. The main researcher, who was responsible for the intervention, did not conduct the interviews, reducing the potential for bias. Furthermore, the identified themes were reviewed by the interviewer to ensure that the interpretations were aligned with the participants' intended meanings [85]. This process of cross-checking served as a form of validation, enhancing the trustworthiness of the analysis.

Table 2 Semi-structured interview guide

Questions
How did the intervention fit into your daily routine?
Did the intervention support your rehabilitation process? Please provide details.
If you could continue with the intervention, would you? Why or why not?
Has the intervention made any impact on your quality of life?
Would you find it difficult to describe this intervention to others? If so, which aspects do you think would be challenging both for you to articulate and for others to comprehend?
What benefits did you notice from participating in the intervention?
Were there any challenges you faced during the intervention at your home?
What potential difficulties might others experience with such interventions?
Based on your experience, what modifications or improvements should be considered for the intervention?

4.2 Safety

4.2.1. The Visual Analog Scale

The Visual Analog Scale (VAS) is a widely used measurement instrument in healthcare research to evaluate subjective experiences such as pain, exhaustion, and overall well-being. It is typically represented as a 10-centimeter line, with one end labeled "no feeling" and the other end labeled "maximum feeling." Participants are asked to indicate the point on the line that corresponds to their current level of sensation. The scores are obtained by measuring the distance (in millimeters) from the "no feeling" end to the participant's mark. This measurement method is a dependable and accurate way of evaluating subjective phenomena [86].

4.3 Efficacy evaluation

4.3.1. Range of motion changes

In the process of assessing the efficacy of the novel telerehabilitation platform, we utilized a quantitative approach to identify any potential changes in ROM from the start to the end of the study. Our primary focus was on ROM values collected from the seated full flexion exercise for the fingers and the active ROM wrist flexion-extension and wrist ulnar-radial deviation active ROM for the wrist joint. The choice to focus on the seated full flexion exercise of the fingers was driven by its frequent repetition throughout the intervention phase. This exercise's recurring presence in the intervention program enabled us to gather ample data, which added a significant degree of reliability to our findings. Furthermore, we undertook an examination of the active ROM associated with wrist flexion-extension as well as wrist ulnar-radial exercises. The selection of these particular exercises originated from our observation that the active ROM for flexion-extension lacks a component of ulnar and radial deviation. To address this gap and ensure a comprehensive evaluation of wrist joint movement, we included the wrist ulnar and radial deviation exercise ROM values. This addition enabled a more holistic understanding of the full range of wrist joint movements facilitated by the novel telerehabilitation platform under evaluation.

4.3.2. Fugl-Meyer Assessment for Upper Extremity

The Fugl-Meyer Assessment for Upper Extremity (FMA-UE) is a widely recognized tool, most used to assess motor impairment in patients who have suffered a hemiplegic stroke [87]. Its high inter-rater reliability and proven validity make it a reliable choice in stroke rehabilitation research and clinical settings. In essence, the FMA-UE evaluation involves 33 distinct items. Each item represents a specific task that the patient is asked to perform. The patient's performance is then scored on a 3-point scale: '0' if the task cannot be performed at all, '1' if the task is only partially performed, and '2' if the task is completely performed. The total score is calculated by adding up the scores of all the individual tasks, providing a quantitative measure of the patient's motor function. A higher score represents better motor function; thus, the FMA-UE score serves as an effective metric of the patient's recovery progress, or the effectiveness of a given rehabilitation intervention.

4.3.3. The Jebsen-Taylor Hand Function Test

The Jebsen-Taylor Hand Function Test (JTHFT) is employed to evaluate the functionality of the hand in performing tasks that mirror activities of daily living (ADLs). This tool has demonstrated reliability and validity in assessing patients with post-stroke hemiparesis. The JTHFT measures the time taken to complete seven different tasks, each of which simulates a specific functional activity related to hand function [88]. These tasks include writing a short sentence, turning over 3x5 inch cards, picking up small objects and placing them in a can, simulated feeding, stacking checkers, picking up large, lightweight objects, and picking up large, heavy objects. The time taken for each task is recorded, and lower times indicate better hand function. Each individual task is timed separately, and these times are then summed up to give an overall performance time.

V. Results

1. Feasibility

1.1. Program completion

The participant demonstrated a high level of adherence to the 8-week home-based program, completing all the assigned 40 sessions. This reflects a strong commitment to the program. On average, each session lasted for approximately 20 minutes. Over the course of the 8-week intervention, the participant performed a series of nine different exercises, totaling 180 repetitions. (Figure 5). The most frequently performed exercises were the Ball Squeeze and Seated Full Flexion, each with 35 repetitions. Given that they completed 40 sessions, the total estimated training time for hand-functional training was 800 minutes (40 sessions x 20 minutes per session) (Figure 6). The participant preferred the asynchronous training method.

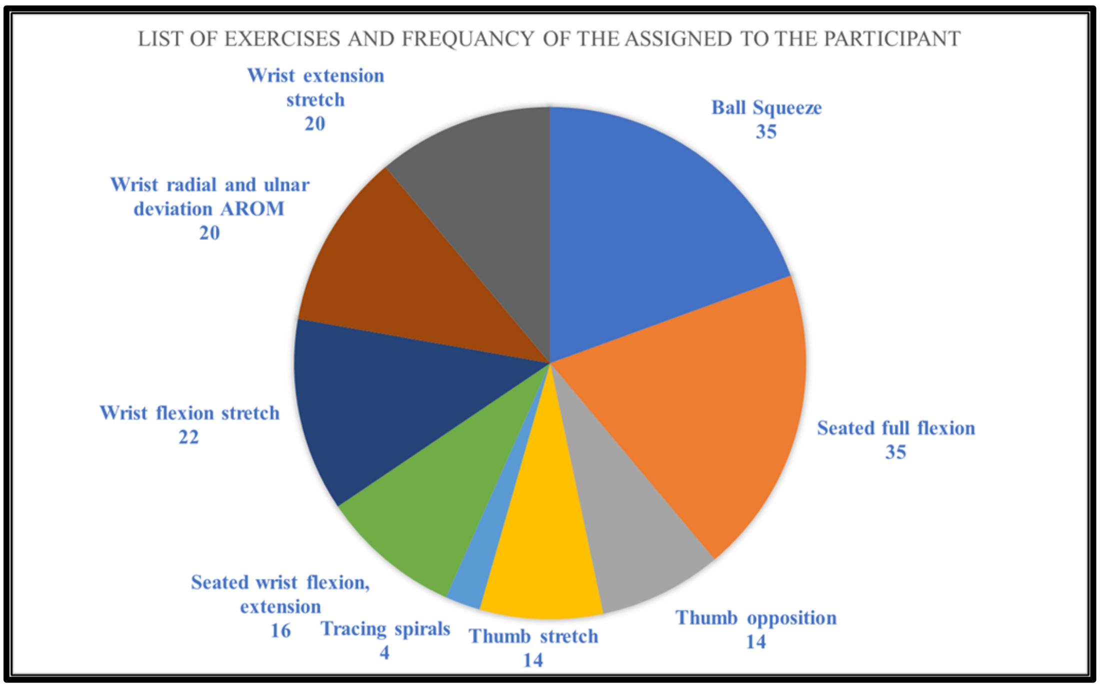

Figure 5 List of exercises and frequency of the assigned to the participant

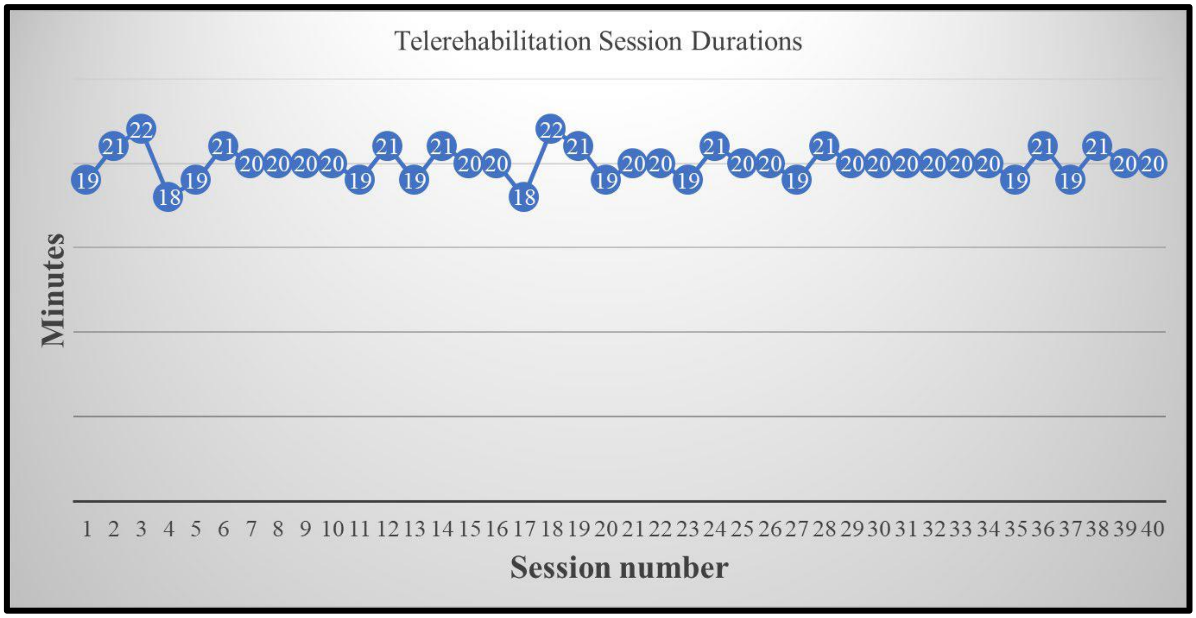

Figure 6 Telerehabilitation Session Durations

1.2. System Usability Scale

The participant reported a SUS score of 77.5 out of 100 for this score indicates good to excellent usability with a strong likelihood that the platform will be accepted intended field [80].

Table 3 SUS responses by the participant

Question	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I think that I would like to use this platform frequently.					✓
I found the iManus platform unnecessarily complex.				✓	
I thought the platform was easy to use.					✓
I think that I would need the support of a technical person to be able to use this system.					✓
I found the various functions in this system were well integrated.				✓	
I thought there was too much inconsistency in this system.	✓				
I would imagine that most people would learn to use this system very quickly.				✓	
I found the system very cumbersome to use.	✓				
I felt very confident using the system.					✓
I needed to learn a lot of things before I could get going with this system.	✓				

1.3. Semi structured interview responses

The results derived from interviews with the participant and caregiver offered insights into the benefits and drawbacks of the iManus platform. These insights were categorized based on the aspects of improvement and challenges reported by the participant and the caregiver.

1.3.1. Perceived benefits.

The participant and caregiver identified several benefits of using the iManus platform. These included enhanced mobility and the sense of control and accountability over therapy.

- Mobility

The participant and caregiver observed an increase in the participant's mobility. The participant stated, "*I feel like I'm more aware of my hand now...using iManus helped me move my hand more in some way.*" The caregiver added, "*I know there have been improvements in her progress... Overall, I believe it's a great tool that made her move her affected hand more and has some clear benefits.*"

- Sense of control and accountability over therapy

The iManus platform has been observed to increase the participant's sense of control in scheduling their therapy sessions. This was made possible as the participant could conveniently use the platform at their own home. This flexibility provided the participant with greater control over their rehabilitation sessions, as noted by the participant: "*Yes, I believe the iManus improved the quality of my life. I mean, it's like getting physio, but at home.*" The caregiver also noticed the convenience offered by the iManus platform, stating: "*it's really convenient because you just need to sit down for 10 minutes at a time. You don't have to go anywhere or get in the car. That's what makes it so great.*" In addition to facilitating a sense of control, the iManus platform was also highlighted by the caregiver for promoting a sense of accountability and commitment in the participant. As the caregiver stated: "*Well, it certainly set up a schedule that needed to be kept. The data being sent through the device keeps a person honest, and there's a sense of commitment and accountability. I think accountability is a significant challenge for many stroke patients.*" These insights are purely based on the statements from the participant and the caregiver.

1.3.2. Perceived barriers

In addition to the reported benefits, the participant and caregiver emphasized certain aspects of the iManus platform that could be improved or posed challenges in its current form. These included: Device Adaptability and Functionality and Ease of Use and Design Suggestions

- Device Adaptability and Functionality

Some aspects of the iManus platform's design presented minor challenges to the participant. The size of the device, particularly the length of the finger components, imposed limitations on the range of exercises they could engage in. The participant shared, *"I had some exercises in mind that I wanted to perform, but I felt that I couldn't do them because the fingers are too long."* Moreover, there were instances where manual intervention from the caregiver was needed to reattach components of the device. The caregiver noted, "These little clips, they keep popping off... I had to assist her in reattaching them."

- Ease of Use and Design Suggestions

Both the participant and the caregiver consistently reported difficulties when putting on and adjusting the glove. The participant suggested that a design closer to a fabric glove could enhance usability. The participant shared, *"I wish that the design was more like a fabric glove so I can easily wear it and do more exercises with it on."* In addition, the participant reported in therapist notes that she felt discomfort during sustained full flexion movements of the thumb, describing it as "*tightness coming from the thumb*". This issue was resolved during the mid-study assessment home visit in which the attachment of the thumb component on the iManus device was adjusted. The caregiver echoed this sentiment, proposing that the design could be further enhanced to simplify the process of wearing and removing the device. As stated by the caregiver, "*When it comes to the actual hand device, it needs to be improved to the point where you can easily slip it on and off without any hassle*."

2. Safety

2.1. Visual Analog scale

The Visual Analog Scale (VAS) was employed to assess our participant's pain levels at three set intervals: before the intervention, immediately after, and midway through the program. Analysis of the gathered data revealed that the utilization of the platform did not result in any increase in reported pain levels by the participant. Throughout the study, the therapist consistently encouraged the participant to communicate any adverse effects experienced, such as pain or edema, resulting from the use of the iManus device. Notably, no instances of pain were reported by the participant, further affirming the absence of adverse effects associated with the intervention.

Table 4 VAS scores to assess pain levels before, during and after the intervention

Visual Analog scale	T0	T1	T2
Score	0	0	0

3. Efficacy evaluation

3.1. Range of motion changes

The ROM values establishes a notable increase in all fingers (Figure 7, Figure 8). This is evident from the measurements taken during the initial and final sessions when these exercises were performed. The Ring Finger MCP Flexion ROM rose from an initial 54.76 degrees to 70 degrees in the final session (~ 29% increase). The Middle Finger MCP Flexion ROM increased from 64 to 74 degrees (~ 15% increase), and the Index Finger MCP Flexion ROM grew from 50 to 57 degrees (~ 14% increase). The Thumb Finger MCP Flexion ROM, although displaying a smaller degree of change, still showed an improvement, increasing from 29 degrees to 32 degrees (~ 10% increase). reveals a mixed pattern of results for the wrist exercises. The Wrist Flexion ROM presented a slight improvement, increasing from 63 to 65 degrees (~ 3% increase). However, the Wrist Extension ROM showed a slight decrease, moving from 35 to 32 degrees (~ 8% decrease). The Wrist Radial Deviation ROM displayed an increase from 7 to 10 degrees (~ 42% increase), and the Wrist Ulnar Deviation ROM also improved, rising from 21 to 24 degrees (~ 14% increase). The listed percentages represent the relative change in ROM for each finger when compared with the first session and last session of the selected exercises.

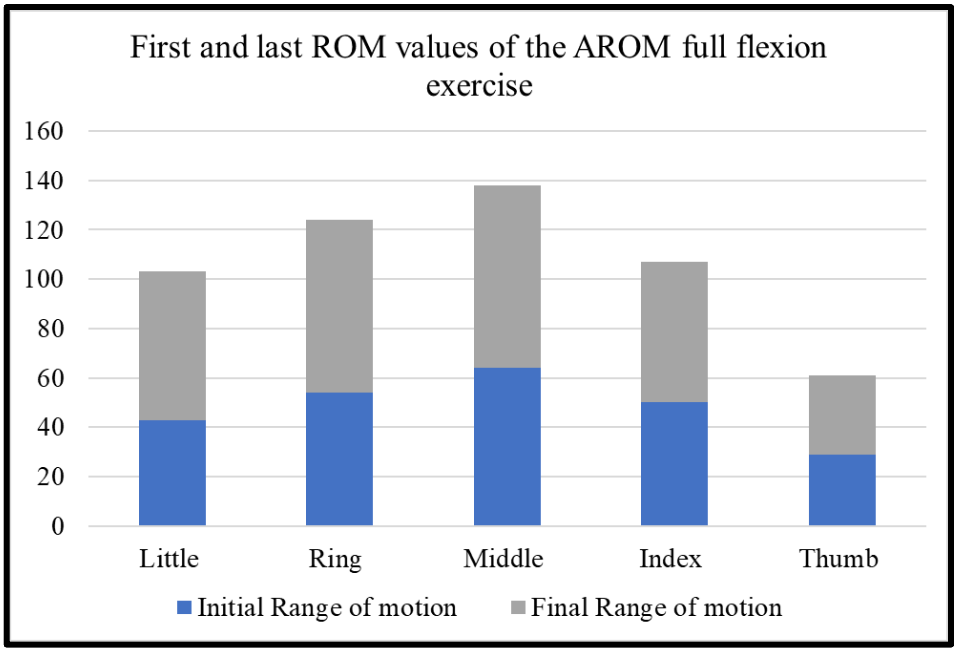

Figure 7 Range of motion values of the AROM of Wrist flexion and extension exercise + Wrist AROM radial and ulnar deviation

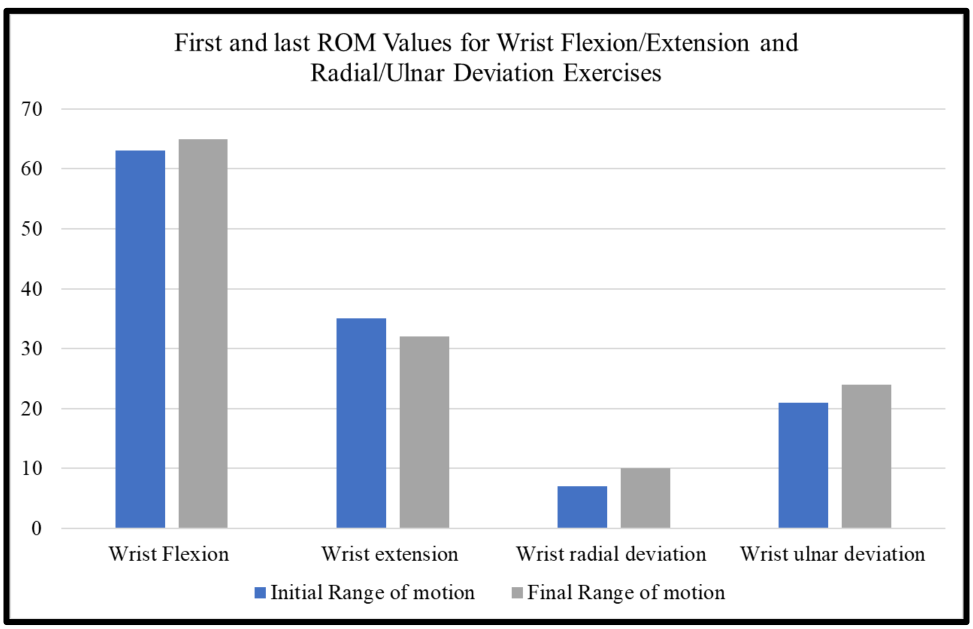

Figure 8 Range of motion values of the AROM of Wrist flexion and extension exercise + Wrist AROM radial and ulnar deviation

3.2. Fugl Meyer Assessment

Table 5 Fugl Meyer Assessment of the Upper Extremity at T0, T1, and T2

	T0	T1	T2
1. Upper extremity	27/36	31/36	31/36
2. Wrist	6/10	6/10	8/10
3. Hand	7/14	11/14	11/14
4. Coordination / Speed	3/6	5/6	6/6
Total 1-4 (motor function)	43	53	56
5. Sensation	8/12	10/12	10/12
6. Passive Joint Motion	12/24	14/24	16/24
7. Joint pain	24/24	24/24	24/24

Table 5 details the scores from the Fugl Meyer Assessment of the upper extremity for a participant at three different time points: T0, T1, and T2. When considering motor function, the scores for the Upper extremity, Wrist, Hand, and Coordination/Speed all increased from T0 to T2. Specifically, the Upper extremity score increased from 27/36 at T0 to 31/36 at both T1 and T2. The Wrist and Hand scores also increased over this period, with final scores of 8/10 and 11/14 at T2, respectively. In the Coordination/Speed category, the participant achieved the maximum score of 6/6 at T2. Sensory perception, as indicated by the Sensation category, showed an increased score at T1 compared to T0. Passive joint motion also increased over time, with scores rising from 12/24 at T0 to 16/24 at T2. The participant reported no joint pain at any of the assessed time points, with consistent scores of 24/24 in the Joint pain category. The data from the Fugl Meyer Assessment suggests an increase in motor function, sensory perception, and joint mobility from T0 to T2.

3.3. Jebsen-Taylor Hand Function Test (JTHFT)

As displayed in Table 6, JTHFT results indicate an overall change in the task completion times across three different stages. Between T0 and T1, reductions in completion times were observed for all tasks except for "Stacking checkers". However, from T1 to T2, an increase in task completion times was noted across all tasks, indicating a slight regression in performance.

Table 6 Jebsen Hand Function Test at T0, T1, and T2

Task	T0	T1	T2
Writing a sentence	35	25	27
Turning over cards	16	15	19
Small common object	34	32	38
Stacking checkers	30	31	36
Simulated feeding	55	42	57
Large light object	25	20	29
Large heavy object	28	23	34
Total score	223	188	240

VI. Discussion

In this feasibility study, we aimed to evaluate a telerehabilitation intervention for hand to assess its safety and efficacy in improving hand function for individuals after a mild stroke. We used a novel platform (iManus) that integrates a smart glove and corresponding software to monitor hand range of motion (ROM) and allows patients to perform rehabilitation exercises at home. During an eight-week intervention with a female participant with a chronic stroke, 40 sessions of hand exercises were performed asynchronously, and outcomes (FMA, JTHFT, VAS) were measured at three different intervals: before, in the middle, and after the intervention. The study also measured changes in range of motion and at after the intervention ended a SUS questionnaire, and a semi-structured interview were done to gather more detailed data about the usability of the intervention and their experience with asynchronous hand training.

The results suggest that the intervention is feasible and the iManus could be used in a larger scale [80]. This was demonstrated by the consistent adherence to the intervention for about 100 minutes per week. Hand function also improved over the course of the training. Interviews with the participant and caregiver depicted what they experienced during the intervention and added further detail to our understanding.

The high adherence to the intervention shows that the participant actively engaged, indicating the feasibility of the intervention [89]. The exact reason for this high treatment adherence is complex, with multiple factors likely at play. The treatment plan adapted to the participant's needs, notably when the participant found a particular exercise that was assigned to improve fine hand motor movements in the hand (tracing spirals) too difficult. As a result, the therapist changed the exercise to an easier one that better suited the participant's abilities. This recognized the participant's feedback and allowed them to participate actively in their treatment. This adaptability may have further encouraged the participant to adhere to the intervention [90]. The availability of numerous exercises in the platform's library, as well as the ability to add exercises that the therapist could not find in the current library, confirms that each stroke patient has unique abilities and different needs [91]. This flexibility fills the gap that exists in some marketed home rehabilitation equipment where users are limited in exercise choices and cannot fully accommodate patients' specific abilities [92].

The participant in this study consistently adhered to the 8-week home-based intervention, completing all the assigned 40 sessions, each lasting an average of 20 minutes. Thus, the exercise duration totaled approximately 800 minutes or about 100 minutes per week (20 minutes per day for 5 days). This suggests that the participant was self-motivated to engage in the exercises without any external motivators, such as scheduled appointments with the therapist for remote supervision. This duration is comparable to or exceeds adherence found in recent studies of home-based, asynchronous upper limb therapy after stroke [93, 94, 95]. The provision of shorter therapy durations, such as 20 minutes, has been shown to enhance accessibility and reduce the sense of overwhelm in telerehabilitation [96]. While existing research points to the potential for more significant functional improvements with higher intensity training [20], the importance of acknowledging the value of a 20-minute session, though brief, should not be understated. These shorter sessions are preferable to no training and have proven to be effective. It must be noted, however, that the referenced 20 minutes pertains solely to the actual training time, excluding activities such as the donning and doffing of the Smart Glove or calibration procedures. These findings contribute to a broader understanding of the flexibility and adaptability inherent in telerehabilitation interventions and provide insights that may guide future research and clinical practice in this domain.

Our approach aimed to remove the restriction to specific training times, making therapy more accessible and allowing for seamless integration into the participant's daily life. This user-centered approach, valued by both the participant and caregiver, prioritized the individual's routine by emphasizing shorter, more manageable sessions. The adaptation of therapy to daily life reduced the burden and contributed to a model of telerehabilitation that underscores flexibility and the individual's unique needs. Furthermore, the heightened mobility noted by both the participant and caregiver could have played a role in the participant's perception of substantial improvement during the intervention. This perception likely promoted a greater commitment to their therapeutic journey and may have been one of the factors that contributed to the participant's sustained adherence to the intervention [97].

In this study, we introduced a unique approach to measure the changes in ROM. Data showed a noticeable improvement in the ROM across all fingers, indicating the effectiveness of the intervention. Significant gains in the ROM of the Ring and Middle Finger could aid in performing intricate tasks that require careful hand control. The thumb plays a significant role in hand function, contributing approximately 40-50% of the entire functionality. Its ability to oppose the other fingers is a major factor in this contribution [98]. Given the crucial role of the thumb in activities such as writing and object manipulation [99,100], even a slight improvement in its ROM can have a significant effect. When interpreting the slight decrease observed in Wrist Extension ROM, it's vital to consider them in the context of the participant's recovery journey, which is distinct and unique. The slight decrease in Wrist Extension ROM might not necessarily signal a setback. This alteration could reflect an adjustment where the participant has started to prioritize Wrist Flexion, a movement often integral to daily tasks [101]. Stroke rehabilitation research indicates that such adaptations are common. Post-stroke, individuals often develop compensatory techniques, such as increased wrist flexion, to mitigate impairments in hand functionality. Additionally, this alteration might suggest the emergence of what's known as flexor synergy patterns, a phenomenon often observed during stroke recovery. This synergy typically combines wrist flexion with finger extension, simplifying the act of grasping and releasing objects [102]. While these synergy patterns might initially assist in achieving functional movement, it's important to acknowledge the potential trade-off. Studies suggest that an over-reliance on these patterns could limit the restoration of independent joint movements and hinder the return to normal movement patterns in the long run [102].

Remotely monitored hand training at home, as implemented in our study, has successfully demonstrated the feasibility of intervening asynchronously. In the present study, the approach facilitated practice without reliance on therapist availability, which could potentially enable an increase in the dose of training in comparison to supervised treatments in clinical settings. The participant was guided to follow the assigned exercises, with particular emphasis on frequency and repetition. This intentional limitation of daily exercises was a strategic measure, rationalized to prevent potential fatigue-related complications. However, future research may consider exploring a more flexible exercise intensity, which could encourage an increased dose of training without compromising the participant's well-being.

Our intervention is novel in that it combines a unique platform and methodology. A comprehensive search of the existing literature did not reveal any studies employing both these specific elements (hand telerehabilitation exoskeleton, asynchronous training) together. However, a study utilizing a comparable platform [103] evaluated the usability of the device for synchronous remote rehabilitation therapy and reported it to be acceptable and showing potential for broader acceptance. Two groups of acute-phase stroke patients were compared: one employing a wearable device along with conventional physical therapy (experimental group) and the other using conventional therapy alone (control group). While no significant differences were found between the groups before the intervention, post-intervention results revealed that the experimental group experienced significantly greater improvements in hand strength, hand function, and daily living activities performance. These findings emphasize the potential efficacy of the platform utilized in our study.

In the research conducted by Nijenhuis, Sharon et al. (2015) [13], the team investigated the feasibility and potential advantages of a home-based, technology-assisted training system for arm and hand rehabilitation in chronic stroke patients. This involved using an arm and hand orthosis, combined with a user interface that was remotely monitored, all set within an engaging gaming context. The study administered this setup to 24 patients over six weeks. It's important to note that the iManus platform used in this study exclusively targets the distal upper extremity (hand) and doesn't assist in movements, unlike the platform used in Nijenhuis study that address both proximal (arm) and distal upper extremities. Nevertheless, their methodology bears resemblance to our approach. Both studies embrace an asynchronous style of training, allowing for self-administered practice without dependence on real-time therapist supervision. In Nijenhuis's research, the findings highlighted the system's feasibility, reflected by an average usability score of 69% and a training duration of 105 minutes weekly. In our study, we observed comparable results, with a usability score of 77.5% and an average training duration of 100 minutes per week. Building on Nijenhuis's results, participants showed improvements in upper extremity function and overall quality of life, as evidenced by specific clinical measures like the Fugl-Meyer score. These outcomes suggest that asynchronous training in stroke telerehabilitation can be effective. The positive results in both studies emphasize the potential benefits of remote, self-administered rehabilitation in enhancing hand function and patient adherence.

A review by Coupar et al. (2012) examined if home-based upper limb therapy could enhance performance in daily activities and upper limb function compared to traditional care. The review investigated four different research projects that examined in-home rehabilitation for the upper limb following a stroke [104]. Their findings showed that these home-based programs were neither more effective nor less effective than similar programs conducted in hospital settings for improving hand motor function. Unlike our study, where the therapist only visited the participant only to record the research outcome measures and allowed them to choose their own training schedule, all the studies included in Coupar's review involved remote supervision at scheduled times. In those cases, the patients had training sessions that were planned and practiced for about five hours or more each week. In the context of this study the participant's experience was closely monitored for any adverse effects. Notably, there was no reported increase in pain levels as assessed by the visual analog scale. This absence of pain increase suggests that the intervention employed in this study can be considered safe. Usability of the system score indicates good to excellent usability with a strong likelihood that the platform will be accepted and used in the intended field [80], but the platform might need improvements, which will be considered for the final version of the platform. The tested prototype of the iManus platform demonstrated some minor design limitations. The participant noted a specific issue concerning the size and length of the finger components. This feedback highlighted a discrepancy in size and length, suggesting that the glove used might not have adequately accounted for variations in hand size and finger length. Interestingly the participant reported this discrepancy primarily due to their wish for the glove to be more compatible with activities of daily living not due to any problem with performing the exercises assigned, this signifies an opportunity for enhancement in the glove's measurements taken for each participant. The participant and caregiver recommended a design modification for the smart glove, suggesting enhanced convenience if it resembled a traditional fabric glove. The spasticity level of our participant, as measured on the Ashworth Scale, was notably low, enabling her to independently put on and remove the glove. Yet, it's crucial to highlight that many stroke patients experience a paretic hand with symptoms of high muscle tone and stiffness, commonly known as spasticity [105, 106]. This prevalent symptom could introduce challenges in the widespread use of this intervention, complicating the act of donning and doffing the hand exoskeletons for stroke survivors. The idea of redesigning the smart glove to mirror the comfort of wearing a traditional fabric glove necessitates thorough research and assessment. While such a design may enhance the user experience, the glove's primary function of collecting accurate data to guide therapists in their clinical decisions must remain uncompromised.

VII. **Limitations**

Based on our preliminary feasibility study focused on a single participant, I recommend conducting a randomized controlled trial for stronger validation. In such study, I suggest dividing participants into two groups: one receiving telerehabilitation using the intervention method we used, and the other undergoing conventional therapy at an outpatient clinic. The focus should ideally be on chronic mild stroke patients. A crucial aspect to explore further would be the cost-effectiveness of each approach. I acknowledge that our current study did not delve into cost analyses, which represents a limitation. Our findings can act as an initial step, guiding more thorough research in the future.

VIII. **Conclusion**

In this study, we evaluated the feasibility, safety and clinical efficacy of a hand telerehabilitation intervention. The results we gathered suggest that post-stroke patients with mild symptoms can benefit from this asynchronous home-based intervention. A significant outcome was the participant's high adherence and the absence of increased pain, coupled with an improvement in hand and wrist range of motion. While the Fugl-Meyer Assessment highlighted promising progress, the Jebsen Hand Taylor Test presented varied results. Supported by an excellent System Usability Scale score, the platform shows promising signs of acceptance in the telerehabilitation field. Through interviews with both the participant and the caregiver, we were able to get their perspective on the intervention. They highlighted key benefits, particularly enhanced mobility and increased sense of control over therapy. Additionally, the participant recommended design enhancements aimed at improving adaptability and user experience. Nevertheless, no significant issues were faced that hindered the intervention's progress. Satisfaction was expressed by both the participant and the caregiver towards the implemented method of rehabilitation.

IX. References

1. World Health Organization. (2004). The atlas of heart disease and stroke. Retrieved from https://apps.who.int/iris/handle/10665/43007.
2. Pollock, A., Farmer, S. E., Brady, M. C., Langhorne, P., Mead, G. E., Mehrholz, J., & van Wijck, F. (2014). Interventions for improving upper limb function after stroke. Cochrane Database of Systematic Reviews, 11. Doi: 10.1002/14651858.CD010820.pub2
3. Feys, H. M., De Weerdt, W. J., Selz, B. E., Cox Steck, G. A., Spichiger, R., Vereeck, L. E., et al. (1998). Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: a single-blind, randomized, controlled multicenter trial. Stroke, 29(4), 785-792. Doi: 10.1161/01.STR.29.4.78
4. Waddell, K. J., Birkenmeier, R. L., Moore, J. L., Hornby, T. G., & Lang, C. E. (2014). Feasibility of high-repetition, task-specific training for individuals with upper-extremity paresis. American Journal of Occupational Therapy, 68(5), 444-453. Doi: 10.5014/ajot.2014.011619
5. Shimodozono, M., Noma, T., Nomoto, Y., Hisamatsu, N., Kamada, K., Miyata, R., et al. (2013). Benefits of a repetitive facilitative exercise program for the upper paretic extremity after subacute stroke: a randomized controlled trial. Neurorehabilitation and Neural Repair, 27(4), 296-305. Doi: 10.1177/1545968312465896
6. Hakkennes, S., & Keating, J. L. (2005). Constraint-induced movement therapy following stroke: A systematic review of randomized controlled trials. Australian Journal of Physiotherapy, 51(4), 221-231.
7. Kwakkel, G., Kollen, B. J., & Wagenaar, R. C. (1999). Therapy impact on functional recovery in stroke rehabilitation: A critical review of the literature. Physiotherapy, 85, 377-391. Doi:10.1016/S0031-9406(05)67198-2
8. Consensus Panel on the Stroke Rehabilitation System. (2007). Time is function. Heart and Stroke Foundation of Ontario.
9. Mima, T., Sadato, N., Yazawa, T., Fukuyama, H., Yonekura, Y., & Shibasaki, H. (1999). Brain structures related to active and passive finger movements in man. Brain, 122(1), 105-110.
10. Carel, C., Loubinoux, I., & Thilman, A. F. (2000). Neural substrate for the effects of passive training on sensorimotor cortical representation: A study with functional magnetic

resonance imaging in healthy subjects. Cerebral Blood Flow & Metabolism, 20(4), 478-484.

11. Woldag, H., & Hummelsheim, H. (2002). Evidence-based physiotherapeutic concepts for improving arm and hand function in stroke patients: A review. Journal of Neurology, 249(5), 518-528.

12. Kwakkel, G., Boudewijn, J., Kollem, E., & Krebs, H. I. (2008). Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. Neurorehabilitation and Neural Repair, 22(2), 111-121.

13. Nijenhuis, S.M., Prange, G.B., Amirabdollahian, F. *et al.* Feasibility study into self-administered training at home using an arm and hand device with motivational gaming environment in chronic stroke. *J NeuroEngineering Rehabil* **12**, 89 (2015). https://doi.org/10.1186/s12984-015-0080-y

14. Lupton D, Seymour W. Technology, selfhood and physical disability. Soc Sci Med. 2000;50(12):1851–62.

15. Fasoli SE, Krebs HI, Hogan N. Robotic technology and stroke rehabilitation: translating research into practice. Top Stroke Rehabil. 2004;11(4):11–9.

16. Maciejasz P, Eschweiler J, Gerlach-Hahn K, Jansen-Troy A, Leonhardt S. A survey on robotic devices for upper limb rehabilitation. J Neuroeng Rehabil. 2014;11:3. doi:10.1186/1743-0003-11-3.

17. Hermens HJ, Vollenbroek-Hutten MMR. Towards remote monitoring and remotely supervised training. J Electromyogr Kinesiol. 2008;18(6):908–19. doi:10.1016/j.jelekin.2008.10.004.

18. Poulin V, Korner-Bitensky N, Dawson DR, Bherer L. Efficacy of executive function interventions after stroke: a systematic review. Top Stroke Rehabil. 2012;19(2):158–171. 18.

19. Askim T, Bernhardt J, Løge AD, Indredavik B. Stroke patients do not need to be inactive in the first two-weeks after stroke: results from a stroke unit focused on early rehabilitation. Int J Stroke. 2012;7:25–31.

20. Kwakkel, G., Kollen, B. J., van der Grond, J., & Prevo, A. J. (2003). Probability of

regaining dexterity in the flaccid upper limb: Impact of severity of paresis and time since onset in acute stroke. Stroke, 34(9), 2181-2186.

21. Coupar, F., Pollock, A., Rowe, P., Weir, C., & Langhorne, P. (2012). Predictors of upper limb recovery after stroke: A systematic review and meta-analysis. Clinical Rehabilitation, 26(4), 291-313.
22. Poulin V, Korner-Bitensky N, Dawson DR, Bherer L. Efficacy of executive function interventions after stroke: a systematic review. Top Stroke Rehabil. 2012;19(2):158–171.
23. Maciejasz P, Eschweiler J, Gerlach-HahnK, Jansen-Troy A, Leonhardt S. A survey on robotic devices for upper limb rehabilitation. J Neuroeng Rehab. 2014;11:3. doi:10.1186/1743-0003-11-3. 20.
24. Balasubramanian, S., Klein, J., & Burder, E. (2010). Robot-assisted rehabilitation of hand function. Current Opinion in Neurology, 23(6), 661-670.
25. Maddahi, A., Choukou, M.-A., Nassiri, A. M., & Maddahi, Y. (2021). A remote training and practicing apparatus and system for upper-limb rehabilitation. United States Patent, US 63/178,735.
26. Veerbeek, J. M., van Wegen, E., van Peppen, R., van der Wees, P. J., Hendriks, E., Rietberg, M., & Kwakkel, G. (2014). What is the evidence for physical therapy poststroke? A systematic review and meta-analysis. PLOS ONE, 9(2), e87987. Doi: 10.1371/journal.pone.0087987
27. Parmet, S., Glass, T. J., & Glass, R. M. (2004). Hemorrhagic Stroke. JAMA, 292(15), 1916. Doi:10.1001/jama.292.15.1916
28. Dewald, J. P., Pope, P. S., Given, J. D., Buchanan, T. S., & Rymer, W. Z. (1995). Abnormal muscle coactivation patterns during isometric torque generation at the elbow and shoulder in hemiparetic subjects. Brain, 118(Pt 2), 495-510. Doi:10.1093/brain/118.2.495
29. Taub, E., Uswatte, G., Mark, V. W., & Morris, D. M. (2006). The learned non-use phenomenon: implications for rehabilitation. Europa Medicophysica, 42, 241-255.
30. Stroke Unit Trialists. (2001). Organised inpatient (stroke unit) care for stroke (Cochrane Review). In The Cochrane Library. Oxford, UK: Update Software.
31. Hutchinson, J. M., & Isaacson, L. G. (2019). Elimination of microglia in mouse spinal cord alters the retrograde CNS plasticity observed following peripheral axon injury. Brain Research, 1721, 146328. https://doi.org/10.1016/j.brainres.2019.146328

32. Mosberger, A. C., Miehlbradt, J. C., Bjelopoljak, N., Schneider, M. P., Wahl, A. S., Ineichen, B. V., Gullo, M., & Schwab, M. E. (2018). Axotomized corticospinal neurons increase supra-lesional innervation and remain crucial for skilled reaching after bilateral pyramidotomy. Cerebral Cortex, 28(2), 625-643. https://doi.org/10.1093/cercor/bhw405

33. Qian, J., Wu, W., Xiong, W., Chai, Z., Xu, X. M., & Jin, X. (2019). Longitudinal optogenetic motor mapping revealed structural and functional impairments and enhanced corticorubral projection after contusive spinal cord injury in mice. Journal of Neurotrauma, 36(3), 485-499. https://doi.org/10.1089/neu.2018.5713

34. Tennant, K. A., Taylor, S. L., White, E. R., & Brown, C. E. (2017). Optogenetic rewiring of thalamocortical circuits to restore function in the stroke-injured brain. Nature Communications, 8, 15879. https://doi.org/10.1038/ncomms15879

35. Rizzi, G., Coban, M., & Tan, K. R. (2019). Excitatory rubral cells encode the acquisition of novel complex motor tasks. Nature Communications, 10(1), 2241. https://doi.org/10.1038/s41467-019-10223-y

36. Wu, F., Xu, K., Liu, L., Zhang, K., Xia, L., Zhang, M., Teng, C., Tong, H., et al. (2019). Vitamin B12 enhances nerve repair and improves functional recovery after traumatic brain injury by inhibiting ER stress-induced neuron injury. Frontiers in Pharmacology, 10, 406. https://doi.org/10.3389/fphar.2019.00406

37. Chen, K., Zheng, Y., Wei, J. A., Ouyang, H., Huang, X., Zhang, F., Lai, C. S. W., Ren, C., So, K. F., & Zhang, L. (2019). Exercise training improves motor skill learning via selective activation of mTOR. Science Advances, 5(7), eaaw1888. Doi: https://doi.org/10.1126/sciadv.aaw1888

38. Luo, L., Zhu, S., Shi, L., Wang, P., Li, M., & Yuan, S. (2019). High intensity exercise for walking competency in individuals with stroke: A systematic review and meta-analysis. Journal of Stroke and Cerebrovascular Diseases, 28(12), 104414. https://doi.org/10.1016/j.jstrokecerebrovasdis.2019.104414

39. Luo, L., Meng, H., Wang, Z., Zhu, S., Yuan, S., Wang, Y., & Wang, Q. (2020). Effect of high-intensity exercise on cardiorespiratory fitness in stroke survivors: A systematic review and meta-analysis. Annals of Physical and Rehabilitation Medicine, 63(1), 59-68. https://doi.org/10.1016/j.rehab.2019.07.006

40. Begg, R., Galea, M. P., James, L., Sparrow, W. A. T., Levinger, P., Khan, F., & Said, C.

M. (2019). Real-time foot clearance biofeedback to assist gait rehabilitation following stroke: A randomized controlled trial protocol. Trials, 20(1), 317. https://doi.org/10.1186/s13063-019-3404-6

41. Melo, R. T. R., Damazio, L. C. M., Lima, M. C., Pereira, V. G., Okano, B. S., Monteiro, B. S., Natali, A. J., Carlo, R. J. D., et al. (2019). Effects of physical exercise on skeletal muscles of rats with cerebral ischemia. Brazilian Journal of Medical and Biological Research, 52(12), e8576. https://doi.org/10.1590/1414-431X20198576

42. Landsmann, B., Pinter, D., Pirker, E., Pichler, G., Schippinger, W., Weiss, E. M., Mathie, G., Gattringer, T., et al. (2016). An exploratory intervention study suggests clinical benefits of training in chronic stroke to be paralleled by changes in brain activity using repeated fMRI. Clinical Interventions in Aging, 11, 97-103. https://doi.org/10.2147/CIA.S95632

43. Schneider, A., Rogalewski, A., Wafzig, O., Kirsch, F., Gretz, N., Kruger, C., Diederich, K., Pitzer, C., et al. (2014). Forced arm use is superior to voluntary training for motor recovery and brain plasticity after cortical ischemia in rats. Experimental and Translational Stroke Medicine, 6(1), 3. https://doi.org/10.1186/2040-7378-6-3

44. Winship, I. R., & Murphy, T. H. (2008). In vivo calcium imaging reveals functional rewiring of single somatosensory neurons after stroke. Journal of Neuroscience, 28(26), 6592-6606. https://doi.org/10.1523/JNEUROSCI.0622-08.2008

45. Mizutani, K., Sonoda, S., Wakita, H., & Shimpo, K. (2015). Protein kinase C activator, bryostatin-1, promotes exercise-dependent functional recovery in rats with cerebral infarction. American

46. Jones, T. A., & Adkins, D. L. (2015). Motor system reorganization after stroke: stimulating and training toward perfection. Physiology, 30(5), 358-370. Doi:10.1152/physiol.00014.2015

47. Okabe, N., Shiromoto, T., Himi, N., Lu, F., Maruyama-Nakamura, E., Narita, K., Iwachidou, N., Yagita, Y., et al. (2016). Neural network remodeling underlying motor map reorganization induced by rehabilitative training after ischemic stroke. Neuroscience, 339, 338-362. Doi:10.1016/j.neuroscience.2016.10.008

48. Koganemaru, S., Sawamoto, N., Aso, T., Sagara, A., Ikkaku, T., Shimada, K., Kanematsu, M., Takahashi, R., et al. (2015). Taskspecific brain reorganization in motor recovery induced by a hybrid-rehabilitation combining training with brain stimulation after stroke.

Neurosci Res, 92, 29-38. Doi:10.1016/j.neures.2014.10.004

49. Plautz, E. J., Barbay, S., Frost, S. B., Friel, K. M., Dancause, N., Zoubina, E. V., Stowe, A. M., Quaney, B. M., et al. (2003). Post-infarct cortical plasticity and behavioral recovery using concurrent cortical stimulation and rehabilitative training: a feasibility study in primates. Neurol Res, 25(8), 801-810. Doi:10.1179/016164103771953880
50. Tennant, K. A., Kerr, A. L., Adkins, D. L., Donlan, N., Thomas, N., Kleim, J. A., & Jones, T. A. (2015). Age-dependent reorganization of peri-infarct "premotor" cortex with task-specific rehabilitative training in mice. Neurorehabil Neural Repair, 29(2), 193-202. Doi:10.1177/1545968314541329
51. Almhdawi, K. A., Mathiowetz, V. G., White, M., & delMas, R. C. (2016). Efficacy of Occupational Therapy Task-oriented Approach in Upper Extremity Post-stroke Rehabilitation. Occupational Therapy International, 23, 444–456. Doi: 10.1002/oti.1438
52. Stroke Foundation. (2022). Clinical Guidelines for Stroke Management. Melbourne, VIC: Author.
53. Lo AC, et al. Robot-assisted therapy for long-term upper-limb impairment after stroke. N Engl J Med. 2010;362 (19):1772–83.
54. Keller U, Klamroth V, van Hedel HJ, Riener R. ChARMin: a robot for pediatric arm rehabilitation. In: Robotics and Automation (ICRA), 2013 I.E. International Conference on. IEEE; 2013. P. 3908–13.
55. Marchal-Crespo L, Michels L, Jaeger L, López-Olóriz J, Riener R. Effect of error augmentation on brain activation and motor learning of a complex locomotor task. Front Neurosci. 2017;11:526.
56. Cesqui B, Aliboni S, Mazzoleni S, Carrozza M, Posteraro F, Micera S. On the use of divergent force fields in robotmediated neurorehabilitation. In: Biomedical Robotics and Biomechatronics, 2008. BioRob 2008. 2nd IEEE RAS & EMBS International Conference on. IEEE; 2008. P. 854–861.
57. Carel C, et al. Neural substrate for the effects of passive training on sensorimotor cortical representation: a study with functional magnetic resonance imaging in healthy subjects. J Cereb Blood Flow Metab. 2000;20(3):478–84.
58. Heuer H, Lüttgen J. Robot assistance of motor learning: a neuro-cognitive perspective. Neurosci Biobehav Rev. 2015;56:222–40.

59. Brunnstrom S. Motor testing procedures in hemiplegia: based on sequential recovery stages. Phys Ther. 1966;46(4):357–75.
60. van Kordelaar J, van Wegen E, Kwakkel G. Impact of time on quality of motor control of the paretic upper limb after stroke. Arch Phys Med Rehabil. 2014;95(2):338–44.
61. Krakauer JW. Motor learning: its relevance to stroke recovery and neurorehabilitation. 56urrO pin Neurol. 2006;19(1):84–90.
62. Cortes JC, et al. A short and distinct time window for recovery of arm motor control early after stroke revealed with a global measure of trajectory kinematics. Neurorehabil Neural Repair.2017;31(6):552–60.Agostini, M., et al. (2015). Telerehabilitation and recovery of motor function: A systematic review and meta-analysis. Journal of Telemedicine and Telecare, 21(4), 202-213. Doi: 10.1258/jtt.2015.
63. Doraiswamy, S., Abraham, A., Mamtani, R., & Cheema, S. (2020). Use of telehealth during the COVID-19 pandemic: Scoping review. Journal of Medical Internet Research, 22(12), e24087.
64. Brennan, D. M., Mawson, S., & Brownsell, S. (2009). Telerehabilitation: Enabling the remote delivery of healthcare, rehabilitation, and self management. Studies in Health Technology and Informatics, 145, 231-248.
65. Piron, L., Turolla, A., Agostini, M., et al. (2009). Exercises for paretic upper limb after stroke: A combined virtual-reality and telemedicine approach. Journal of Rehabilitation Medicine, 41(12), 1016-1102.
66. Duncan, P. W., & Telerehabilitation, B. J. (2021). Has its time come? Stroke, 52(8), 2694-2696.
67. Watts, G. (2020). COVID-19 and the digital divide in the UK. Lancet Digital Health, 2(8), e395-e396.
68. Laver, K. E., Adey-Wakeling, Z., Crotty, M., Lannin, N. A., George, S., & Sherrington, C. (2020). Telerehabilitation services for stroke. Cochrane Database of Systematic Reviews, 1(1), CD010255.
69. Thomas, J., Barraket, J., Wilson, K., et al. (2020). Measuring Australia's digital divide: The Australian digital inclusion index.
70. Australian Bureau of Statistics. (2018). Household Use of Information Technology. Canberra, ACT: ABS.

71. Towfighi, A., Benson, R. T., Tagge, R., Moy, C. S., Wright, C. B., & Ovbiagele, B. (2020). Inaugural health equity and actionable disparities in stroke: Understanding and problem-solving symposium. Stroke, 51(11), 3382-3391.

72. Peretti, A., Amenta, F., Tayebati, S. K., Nittari, G., Mahdi, S. S. (2017). Telerehabilitation: Review Of the State-of-the-art And Areas Of Application. JMIR Rehabilitation and Assistive Technologies, 2(4), e7. https://doi.org/10.2196/rehab.7511

73. Chittim, G., Pappas, A., & Bomba, J. (2020). The Changing Fortunes of Telemedicine in Europe—Past, Present, and Future beyond COVID-19. Health Advances.

74. Meseguer-Henarejos, A. B., Sánchez-Meca, J., López-Pina, J. A., & Carles-Hernández, R. (2018). Inter- and intra-rater reliability of the Modified Ashworth Scale: a systematic review and meta-analysis. *European journal of physical and rehabilitation medicine*, *54*(4), 576–590. https://doi.org/10.23736/S1973-9087.17.04796-757

75. Li, H., Jia, J., & Yang, Z. (2016). Mini-Mental State Examination in Elderly Chinese: A Population-Based Normative Study. *Journal of Alzheimer's disease : JAD*, *53*(2), 487–496. https://doi.org/10.3233/JAD-160119

76. Nakase-Thompson, R. (2004). The Mississippis Aphasia Screening Test. The Center for Outcome Measurement in Brain Injury.

77. G. S. K. Wood-Dauphinee, "The impact of rehabilitation on stroke outcomes: What's the evidence?," in Recovery After Stroke, B. H. M. P. D. Barnes and J. Bogousslavsky, Eds. Cambridge, U.K.: Cambridge Univ. Press, 2005, pp. 668–.

78. R. P. Van Peppen, G. Kwakkel, S. Wood-Dauphinee, H. J. Hendriks, P. J. Van der Wees, and J. Dekker, "The impact of physical therapy on functional outcomes after stroke: What's the evidence?," Clin. Rehabil., vol. 18, pp. 833–862, 2004.

79. S. L. Wolf, C. J. Winstein, J. P. Miller, E. Taub, G. Uswatte, D. Morris, C. Giuliani, K. E. Light, and D. Nichols-Larsen, "Effect of constraintinduced movement therapy on upper extremity function 3 to 9 months after stroke: The EXCITE randomized clinical trial," JAMA, vol. 296, pp. 2095–2104, 2006.

80. Bangor, A., Kortum, P., & Miller, J. (2008). An Empirical Evaluation of the System Usability Scale. International Journal of Human–Computer Interaction, 24, 574 – 594.

https://doi.org/10.1080/10447310802205776.

81. Creswell, J. W., & Poth, C. N. (2017). Qualitative inquiry and research design: Choosing among five approaches. Sage publications.
82. Desmet, P., & Hekkert, P. (2007). Framework of product experience. International Journal of Design, 1(1), 57-66.
83. Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Quarterly, 13(3), 319-340.
84. Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. American journal of evaluation, 27(2), 237-246.
85. Tong, A., Sainsbury, P., & Craig, J. (2007). Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. International Journal for Quality in Health Care, 19(6), 349-357.
86. Jensen, M. P., McFarland, C. A., & Turner, J. A. (2011). Visual Analog Scale (VAS) in Pain Measurement. Journal of Pain and Symptom Management, 42(2), 157-168.
87. Gladstone, D. J., Danells, C. J., & Black, S. E. (2002). The Fugl-Meyer assessment of motor recovery after stroke: a critical review of its measurement properties. Neurorehabilitation and Neural Repair, 16(3), 232-240.
88. Jebsen, R., Taylor, N., Trieschmann, R., Trotter, M., & Howard, L. (1969). An objective and standardized test of hand function. Arch Phys Med Rehabil, 50, 311-319.
89. Hoaas, H., Andreassen, H., Lien, L. A., Hjalmarsen, A., Zanaboni, P. (2016). Adherence and Factors Affecting Satisfaction In Long-term Telerehabilitation For Patients With Chronic Obstructive Pulmonary Disease: A Mixed Methods Study. BMC Medical Informatics and Decision Making, 1(16). https://doi.org/10.1186/s12911-016-0264-9.
90. Duncan, Pamela W., et al. "Measurement Of Motor Recovery After Stroke. Outcome Assessment and Sample Size Requirements.". Stroke, vol. 23, no. 8, 1992, p. 1084-1089. https://doi.org/10.1161/01.str.23.8.1084
91. Friedman, N., Chan, V., Reinkensmeyer, A.N. *et al.* Retraining and assessing hand movement after stroke using the MusicGlove: comparison with conventional hand therapy

and isometric grip training. *J NeuroEngineering Rehabil* **11**, 76 (2014). https://doi.org/10.1186/1743-0003-11-76.

92. Donoso Brown EV, McCoy SW, Fechko AS, Price R, Gilbertson T, Moritz CT. Preliminary investigation of an electromyography-controlled video game as a home program for persons in the chronic phase of stroke recovery. Arch Phys Med Rehabil. 2014;95(8):1461–9.

93. Standen PJ, Threapleton K, Connell L, Richardson A, Brown DJ, Battersby S, et al. Patients' use of a home-based virtual reality system to provide rehabilitation of the upper limb following stroke. Phys Ther. 2014;11:11.

94. Sivan M, Gallagher J, Makower S, Keeling D, Bhakta B, O'Connor RJ, et al. Home-based Computer Assisted Arm Rehabilitation (hCAAR) robotic device for upper limb exercise after stroke: results of a feasibility study in home setting. J Neuroeng Rehabil. 2014;11(1):163. doi:10.1186/1743-0003-11-163.

95. Nelson, M. T., Russell, T., Crossley, K. M., Bourke, M. J., McPhail, S. M. (2019). Cost-effectiveness Of Telerehabilitation Versus Traditional Care After Total Hip Replacement: a Trial-based Economic Evaluation. Journal of Telemedicine and Telecare, 6(27), 359-366. https://doi.org/10.1177/1357633x19869796

96. Tan, Mingyang, et al. "Analysis Of the Current Status Of Rehabilitation Motivation And Its Influencing Factors In Older Adults With Stroke: A Cross-sectional Study". Frontiers in Aging Neuroscience, vol. 15, 2023. https://doi.org/10.3389/fnagi.2023.1186681.

97. Aubin PM, Sallum H, Walsh C, Stirling L, Correia A. A pediatric robotic thumb exoskeleton for at-home rehabilitation: the Isolated Orthosis for Thumb Actuation (IOTA). In: IEEE International Conference on Rehabilitation Robotics: [proceedings], vol. 2013; 2013. p. 6650500.

98. Edmunds JO. Current concepts of the anatomy of the thumb trapeziometacarpal joint. J Hand Surg Am. 2011;36:170–82.

99. Olafsdottir H, Zatsiorsky VM, Latash ML. Is the thumb a fifth finger? A study of digit interaction during force production tasks. Exp Brain Res. 2005;160:203–13

100. Teasell R, Meyer MJ, McClure A, Pan C, Murie-Fernandez M, Foley N, Salter K. Stroke

rehabilitation: an international perspective. Topics in stroke rehabilitation. 2009 Jan 1;16(1):44-56.

101. d'Avella A, Saltiel P, Bizzi E (2003) Combinations of muscle synergies in the construction of a natural motor behavior. Nat Neurosci 6: 300–308.

102. Kwakkel, G., Kollen, B., & Lindeman, E. (2004). Understanding the pattern of functional recovery after stroke: facts and theories. Restorative neurology and neuroscience, 22(3-4), 281-299.

103. Park, Yun-Sang et al. "Effects of a Rehabilitation Program Using a Wearable Device on the Upper Limb Function, Performance of Activities of Daily Living, and Rehabilitation Participation in Patients with Acute Stroke." *International journal of environmental research and public health* vol. 18,11 5524. 21 May. 2021, doi:10.3390/ijerph18115524

104. Coupar F, Pollock A, Legg LA, Sackley C, van Vliet P. Home-based therapy programmes for upper limb functional recovery following stroke. Cochrane Database Syst Rev. 2012;5:CD006755. doi: 10.1002/14651858.CD006755.pub2

105. Chen, H.-M., Chen, C. C., Hsueh, I. P., Huang, S. L., and Hsieh, C. L. (2009). Test-retest reproducibility and smallest real difference of 5 hand function tests in patients with stroke. Neurorehabilitation neural repair 23 (5), 435–440. doi:10.1177/1545968308331146

106. Yap, H. K., Lim, J. H., Goh, J. C. H., and Yeow, C. H. (2016b). Design of a soft robotic glove for hand rehabilitation of stroke patients with clenched fist deformity using inflatable plastic actuators. J. Med. Devices 10 (4). doi:10.1115/1.403 3035