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Research article

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

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ABSTRACT

Background: Patients with stroke often experience weakened upper limbs, making daily tasks difficult to perform. Although rehabilitation devices are available, patients often relapse post-discharge due to insufficient practice. We present a home-based hand telerehabilitation intervention using the iManus™ platform comprising a sensorized glove, a mobile app for the patients, and a therapist portal for monitoring patient progress.
Objectives: 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. A qualitative approach was also 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 their informal caregiver. Safety was evaluated by monitoring pain levels using the Visual Analog Scale (VAS), and efficacy was determined by observing the changes in the fingers' 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: Our participant completed all the assigned sessions, with each averaging 20 min. Usability scored 77.5 out of 100 on the SUS. User feedback from the interviews revealed improved mobility and control over therapy as benefits, 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.
Conclusions: This single case study demonstrated the preliminary feasibility, safety, and efficacy of a novel home-based hand intervention for stroke survivors. The participant showed improved hand functions, good adherence to the program, and reported satisfaction with the intervention. However, these results are based on a single-case study, and further large-scale studies are needed before any generalization is recommended.

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1. Introduction

According to the World Health Organization, 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. Stroke patients often struggle with the challenge of regaining full functionality of their limbs, especially their hands. 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 [20–22].

A series of rehabilitation techniques have been developed and refined over the last 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. Despite the plethora of physiotherapy interventions at their disposal, a significant number of these patients fail to achieve optimal hand use. This challenge is further exacerbated for those without access to therapy, leading them to underutilize their affected hands even more. This stresses the need to understand the underlying reasons and to explore potential solutions. Each of these treatments has a lot of theoretical advocates, and each has clinically been proven to be successful; for example, constraint-induced movement Therapy improves mobility on the affected side, according to several studies [1,5]. In their everyday lives, participants who underwent Constraint Induced Movement Therapy 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. A plausible procedure to enhance rehabilitation services is telerehabilitation, a subset of telehealth, that encapsulates the remote delivery of rehabilitation services. This spectrum ranges from consultations and assessments to intricate therapeutic programs, facilitated through an array of digital mediums, including real-time videoconferencing and email-based communication. In certain research contexts, this is further augmented with sensors, wearable devices, and interactive gaming strategies. 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. Devices like hand telerehabilitation systems, which provide performance feedback, increase 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 supervision. The constraints imposed by the pandemic have significantly reduced the traditional access channels to rehabilitation services, both in hospitals and communities. This has illuminated telerehabilitation as a viable alternative, both to improve care and to mitigate the spread of the disease. This transition, while promising, is riddled with challenges, complexities, and compromises that need to be navigated with care. 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.

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 [9–11]. 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 recovery [12]. Furthermore, with the incidence of stroke expected to rise significantly over the next 20 years [8], so will the demand for therapy. This paper describes an at-home hand rehabilitation intervention based on a novel portable platform: *iManus*™ [25] (iManus), 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 distal upper extremity dysfunctions by providing a tailored treatment plan through the dedicated software, 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 and finger joints). iManus also provides therapists with the option of synchronous (under therapist supervision) and asynchronous (no therapist supervision needed) therapy sessions, and both have specific benefits to the patient and therapist whether in a clinic or at home especially since the platform allows for live chat between the therapist and patient when needed. The goal of the presented study was to examine the 1) feasibility, 2) safety, and 3) clinical efficacy of a home-based telerehabilitation intervention, in improving distal upper extremity 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.

2. Methods

2.1. Proposed technology to support at-home hand telerehabilitation

iManus is a novel hand monitoring and telerehabilitation platform, tailored for individuals with distal upper extremity mild dysfunctions. Developed in collaboration between Tactile Robotics Ltd. and the corresponding author of this paper from the University of Manitoba, its primary goal is to offer a holistic functional rehabilitation experience, emphasizing real-time feedback, visual indicators, and personalized treatment plans. This approach aids users in increasing the activity of their affected hand post-hemiplegia, mirroring and advancing the experience of in-clinic therapy. The platform is made of a Sensorized Smart Glove (hardware component), and a desktop portal (therapist interface).

The core feature of iManus is a sensor-integrated smart glove connected to a dedicated smartphone app (Fig. 1). Constructed from elastic-plastic and tailored to the user's hand dimensions, the glove incorporates flex sensors. The photos presented in Fig. 1 are more recent than the version used in this study which may present different levels of comfortability when wearing the glove. These sensors are designed to monitor the flexion and extension ROM for both metacarpophalangeal (MCP) and wrist joints. Data collected by the glove, calibrated with a 0° baseline for neutral joint angles, is then converted into a format optimized for clinical evaluation. Preliminary tests confirm the glove's ability to effectively record joint ROM, though further research is needed to capture the full ROM across all finger joints. The patient mobile application is available on both iOS and Android. The iManus patient app is a bridge between therapists and patients. It showcases the exercise videos, prescribed repetitions, sets, and rest periods assigned by their therapist. An insightful design lets patients pause exercises if needed and includes a chat feature for direct communication with therapists. Emphasis has been placed on ensuring the app's design remains user-friendly and easy to use. Additionally, robust data security measures are implemented to safeguard sensitive medical information.

The therapist interface, an integral component of the iManus platform, is a web-based portal equipped with tools for hand rehabilitation. It features therapy assessment forms and a vast exercise library focusing on the distal upper extremity for hemiplegic patients. Therapists can manage patient lists, and session schedules, and assign exercises with their desired frequency and intensity (Fig. 2). A standout feature is the 3D hand model that mirrors the patient's hand movements during exercises, assisting therapists in gauging the accuracy of exercise execution.

iManus™ offers two distinct ways of how the sessions are carried out: synchronous and asynchronous communication modality. The synchronous mode allows real-time engagement between the therapist and patient, facilitated by a live webcam feature. This ensures immediate feedback during exercise execution. In contrast, the asynchronous mode provides patients the flexibility to perform exercises at their convenience, with therapists reviewing the data and exercises from the platform at a suitable time, ensuring a comprehensive assessment of progress.

2.2. Participant

This paper presents a feasibility study that examines all aspects of the novel proposed intervention, encompassing technical and logistical considerations. Therefore, we proceeded cautiously by limiting the recruitment to one participant before expanding to a larger-scale clinical trial. Our participant is a 55-year-old woman who experienced a stroke in March of 2021 and has mild upper

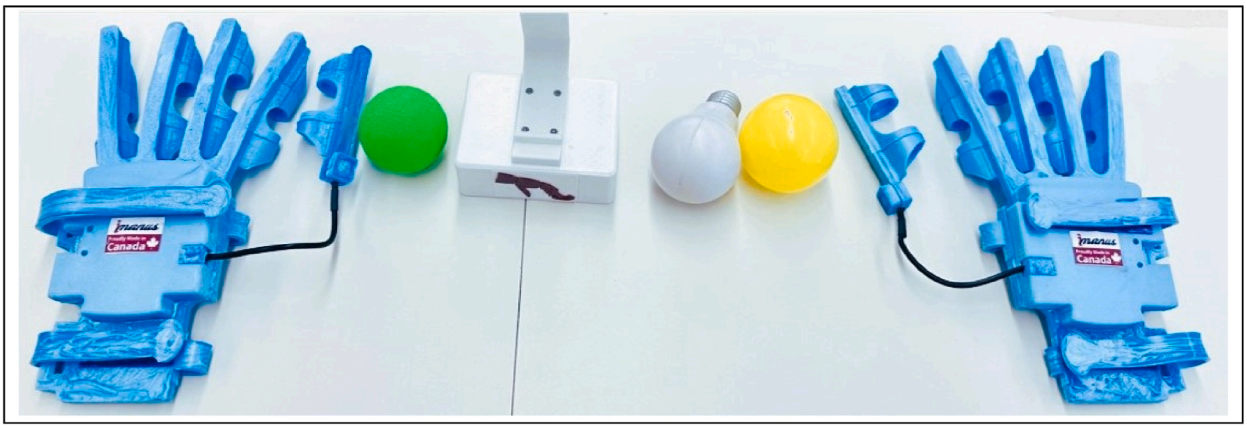

Fig. 1. iManusTM (https://www.theimanus.com/).

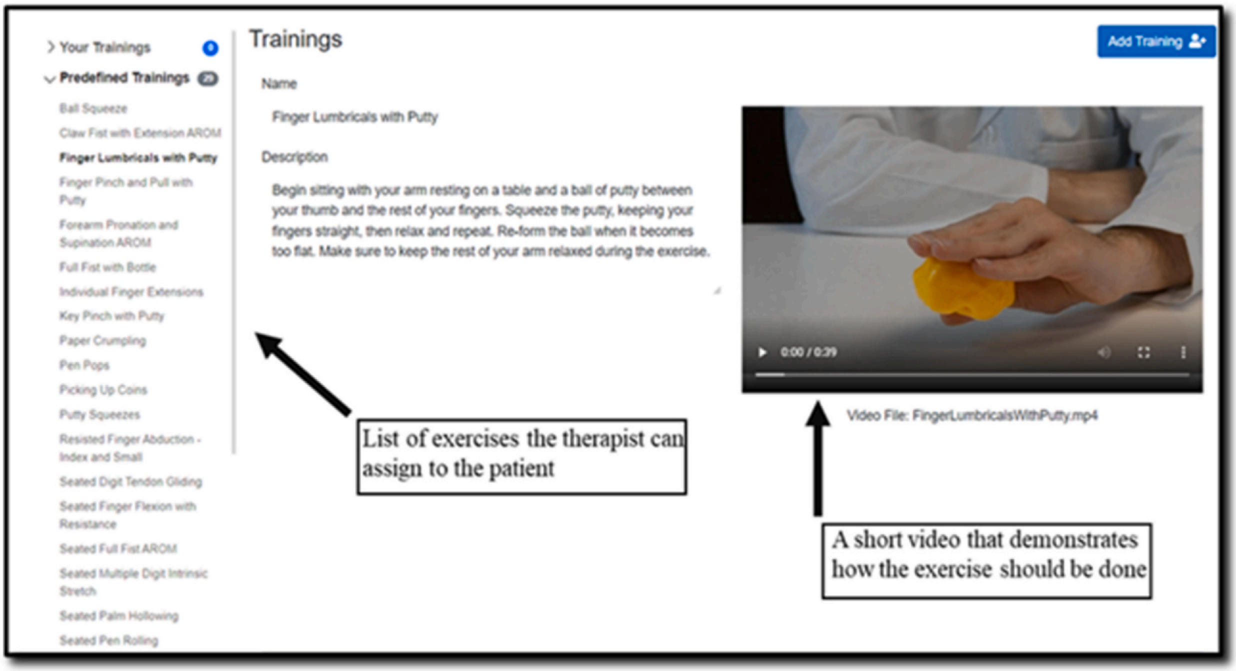

Fig. 2. iManus library of exercises.

extremity dysfunction due to a unilateral brain lesion. The participant can flex the shoulder, extend the elbow and display limited hand opening with some capacity for partial movements. Her Mini-Mental State Examination score was 30/30. She had no contraindications to intensive hand training, upper limb pain, bilateral paresis, adverse hand skin conditions, or sensory impairments that could interfere with platform use. The participant completed a written informed consent before being involved in the study. The research protocol, summarized in Fig. 3, was approved by the ethics committee at the University of Manitoba Health Research Ethics Board [#H2019:074 (HS22607)].

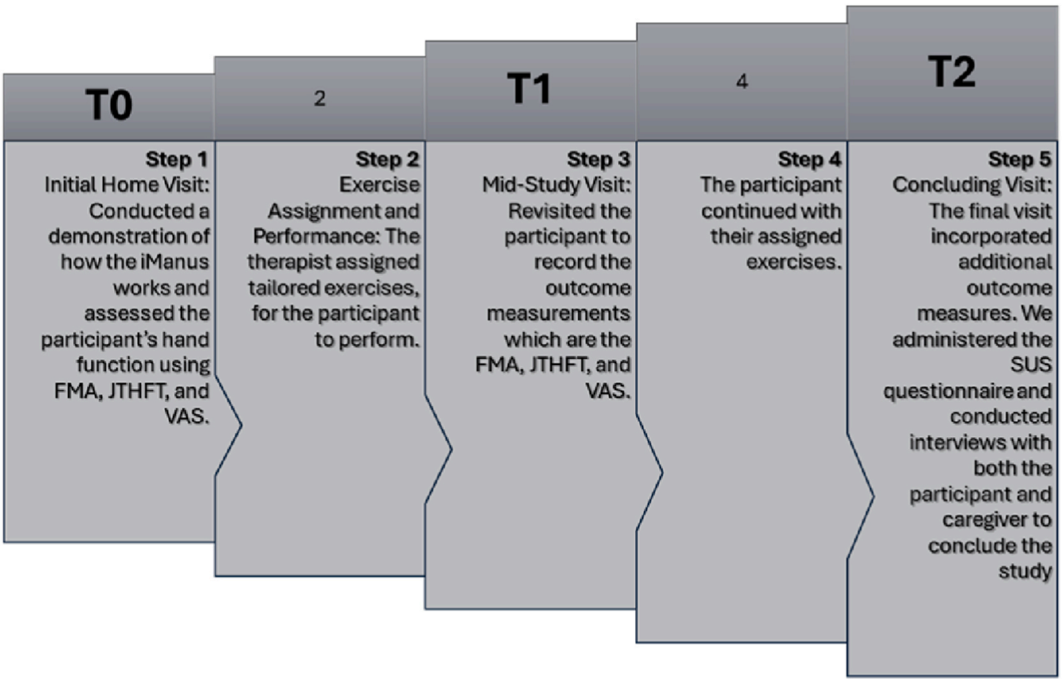

Fig. 3. Description of the intervention.

2.3. 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 the caregiver and participant were proficient in operating iManus effectively.

2.4. Intervention and study design

In our feasibility study, we implemented a personalized treatment plan for a chronic stroke participant over two months, with telerehabilitation sessions recommended five times weekly for 30 min each. Our exercise selection was based on the assessment done by the therapist and rooted in task-oriented arm training, emphasizing functional skill re-acquisition. The selection of exercises primarily originated from our observation that the active range of motion for flexion-extension lacks a component of ulnar and radial deviation. To address this gap, a combination of passive and active hand movements was proposed. The chosen exercises, as outlined in Fig. 4, were assigned to cover a comprehensive range of movements. In our approach, we encouraged the participant's autonomy and engagement by involving them actively in the exercise selection process and asking if they would like some exercises modified. The participant also had complete autonomy in deciding their session schedule. The number of repetitions, sets, and rest periods were initially determined by the therapist for each exercise as an optimal scenario. However, the therapist had the flexibility to adjust these parameters by reducing repetitions, sets, or extending rest periods based on the patient's pain level, fatigue, or motivation. These variables varied from session to session, but progression between sessions was carefully monitored to achieve adaptations that advanced the participant from week to week. This collaborative method was aimed at fostering a sense of autonomy and promoting adherence, potentially leading to enhanced outcomes. Given the choice between synchronous and asynchronous sessions, the participant opted for asynchronous interactions on the iManus platform, favouring a more flexible approach to their rehabilitation without the direct involvement of the therapist. The dynamic treatment plan was adjusted based on feedback, therapist observations, and device-derived ROM values. The therapist would regularly access the portal daily to look for messages received from the participant. Quick feedback was provided after each session, with more comprehensive feedback given weekly to discuss performance from the previous week and outline plans for the following week. Additionally, the therapist would use the interface to remotely monitor the participant's advancement, adherence to the training program, and the duration of their training sessions. Nevertheless, it is important to acknowledge that in this specific approach, we did not attempt to include external motivational incentives to enhance the participant's adherence to the intervention.

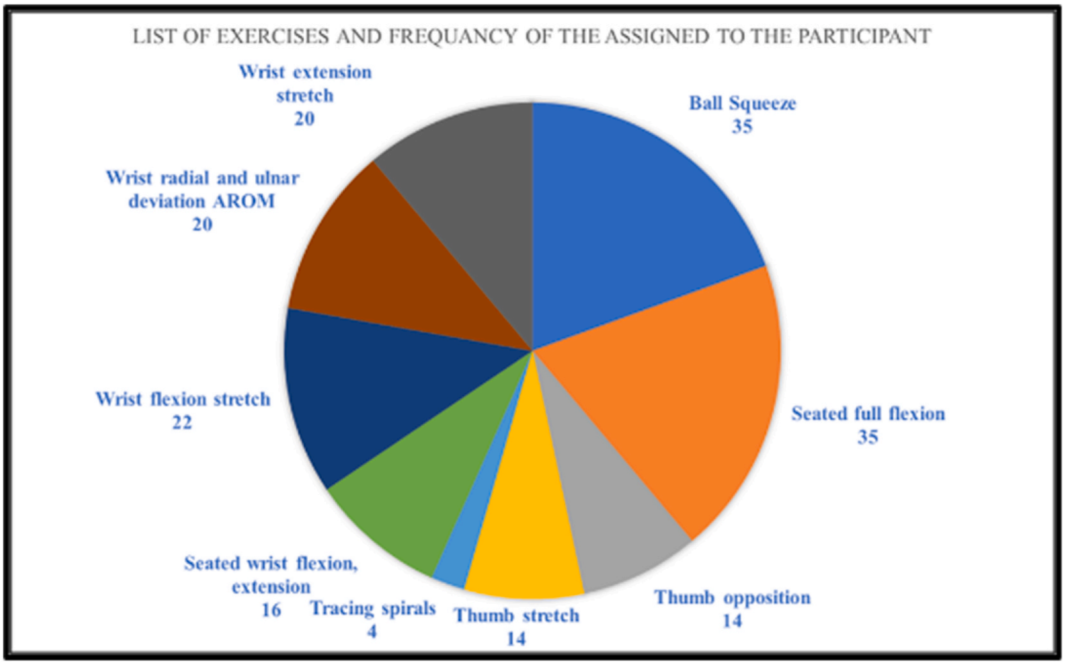

Fig. 4. List of exercises and frequency of the assigned to the participant.

2.5. 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. 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.

2.6. Outcome measures

- **Feasibility:** Feasibility was primarily assessed through three key metrics. Firstly, the participant's adherence to the therapist's instructions, which entailed training five times a week for eight weeks, served as a direct reflection of user acceptance of the intervention. Consistent adherence indicates a positive reception and the practicality of the intervention. Secondly, the System Usability Scale (SUS) questionnaire was employed. A favourable SUS score not only underscores user acceptance but also suggests that the platform is poised for broader implementation, given its potential appeal to a wider audience. Lastly, to delve deeper into the participant's experience with the telerehabilitation program, two post-intervention semi-structured interviews were conducted with both the patient and their caregiver. Utilizing an interview guide, shaped by the User Experience and Acceptance Models, ensured that while specific topics were thoroughly explored, the overarching research objectives remained in focus.
- **Safety:** To assess the safety of the intervention we used 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-cm line, with one end labelled "no feeling" and the other end labelled "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 millimetres) from the "no feeling" end to the participant's mark.
- **Clinical efficacy:** To evaluate the intervention's effectiveness, we primarily focused on three metrics: changes in Range of Motion (ROM) in the finger and wrist joints, scores from the Fugl-Meyer Assessment for Upper Extremity (FMA-UE), and results from the Jebsen-Taylor Hand Function Test (JTHFT). To initiate our evaluation, we analyzed the changes in the Range of Motion (ROM) for both wrist and MCP joints. The exercises chosen for analyzing ROM changes were selected based on two key criteria. First, each exercise needed to have a distinct movement involving either the wrist or MCP joints to ensure that the ROM could be measured. Second, we opted for exercises that were consistently performed throughout the study, allowing us to monitor changes in ROM over the longest possible time frame. The FMA-UE, a well-established tool for assessing motor impairment in stroke patients, provided a quantitative measure of motor function, with higher scores indicating enhanced motor capabilities. Lastly, the JTHFT, which assesses hand functionality in tasks resembling daily activities, measured the time taken for various tasks, with shorter durations signifying improved hand function.

3. Results

- **Feasibility**
  - *Program completion*: The participant demonstrated a high level of adherence to the 8-week home-based program, completing all the assigned 40 asynchronous sessions (Table 1). On average, each session lasted for 20 minutes. The intervention involved a total of 180 exercise repetitions distributed across various exercises. 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 min (40 sessions x 20 min per session).

- How did the intervention fit into your daily routine?

Table 1
An overview of the 8-week home-based telerehabilitation program detailing session frequency, duration, and exercise specifics.

- *System Usability Scale*: The participant reported a SUS score of 77.5 out of 100. This score indicates good to excellent usability with a strong likelihood that the platform will be accepted intended field [26].
- *Semi-structured interview responses*: The results derived from interviews with the participant and caregiver offered insights into the benefits and barriers of the hand telerehabilitation intervention. These insights were categorized based on the aspects of improvement and challenges reported by the participant and the caregiver. The following questions formed the interview guide:

Category	Details
Program Duration	8 weeks
Total Sessions	40 sessions
Average Session Time	20 min
Most Frequent Exercises	Ball Squeeze and Seated Full Flexion
Repetitions for Most Frequent Exercises	35 repetitions each
Total Training Time	800 min (40 sessions x 20 min/session)
Training Method	Asynchronous

- Did the intervention support your rehabilitation process? Please discuss 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?

- *Perceived benefits*: The participant and caregiver identified several benefits of using the iManus platform. These included enhanced mobility and a 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 of the intervention method, stating: "*it's convenient because you just need to sit down for 10 min 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 ROM monitoring aspect 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.
- *Perceived barriers:* In addition to the reported benefits, the participant and caregiver emphasized certain aspects of the smart glove that could be improved in the final version of the product. Both the participant and their caregiver reported minor challenges when putting on and adjusting the glove at the beginning of the study. 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.*"

- **Safety**

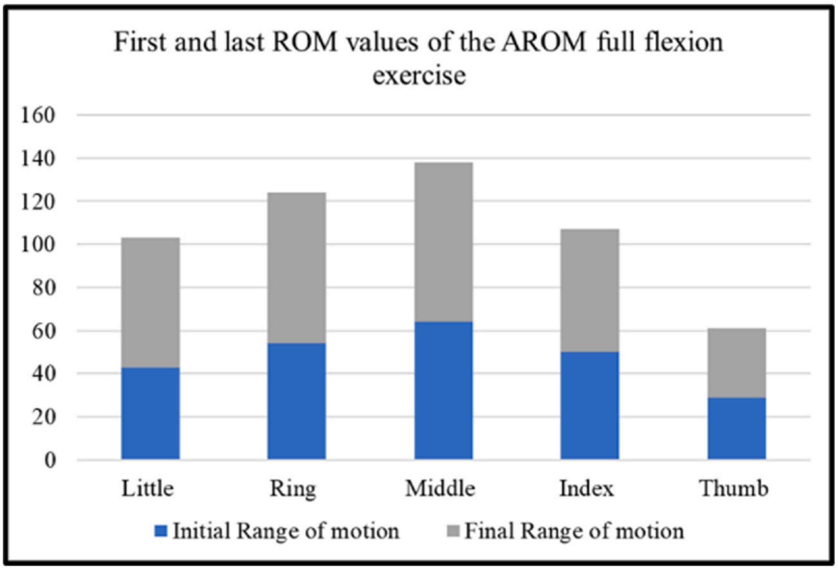

Fig. 5. Range of motion values of the AROM of Wrist flexion and extension exercise + Wrist AROM radial and ulnar deviation.

- *Pain level*: A 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.

- **Clinical efficacy**

- *Range of motion changes: the observation of the* ROM values indicate an overall improvement of finger function (Figs. 5 and 6). Measurements from initial to final sessions showed that: Ring Finger MCP Flexion increased by ~29 % (54.76–70°), Middle Finger MCP by ~15 % (64–74°), Index Finger MCP by ~14 % (50–57°), and Thumb MCP by ~10 % (29–32°). Wrist exercises showed mixed results: Wrist Flexion improved by ~3 % (63–65°), Wrist Extension decreased by ~8 % (35–32°), Wrist Radial Deviation increased by ~42 % (7–10°), and Wrist Ulnar Deviation by ~14 % (21–24°). Percentages reflect relative ROM changes from the first to the last session.
- *Fugl Meyer Assessment:* Table 2 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.

4. Discussion

In the last decade, stroke physiotherapy has advanced through expanding research, enhancing evidence-backed interventions, and improving patient outcomes. Emphasizing innovative, evidence-supported interventions enriches our understanding of diverse outcomes. Telerehabilitation complexities, especially in hand recovery, must be addressed. The COVID-19 pandemic has accelerated the shift to telehealth, driven by the need to sustain health services and the widespread use of videoconferencing technologies. In our

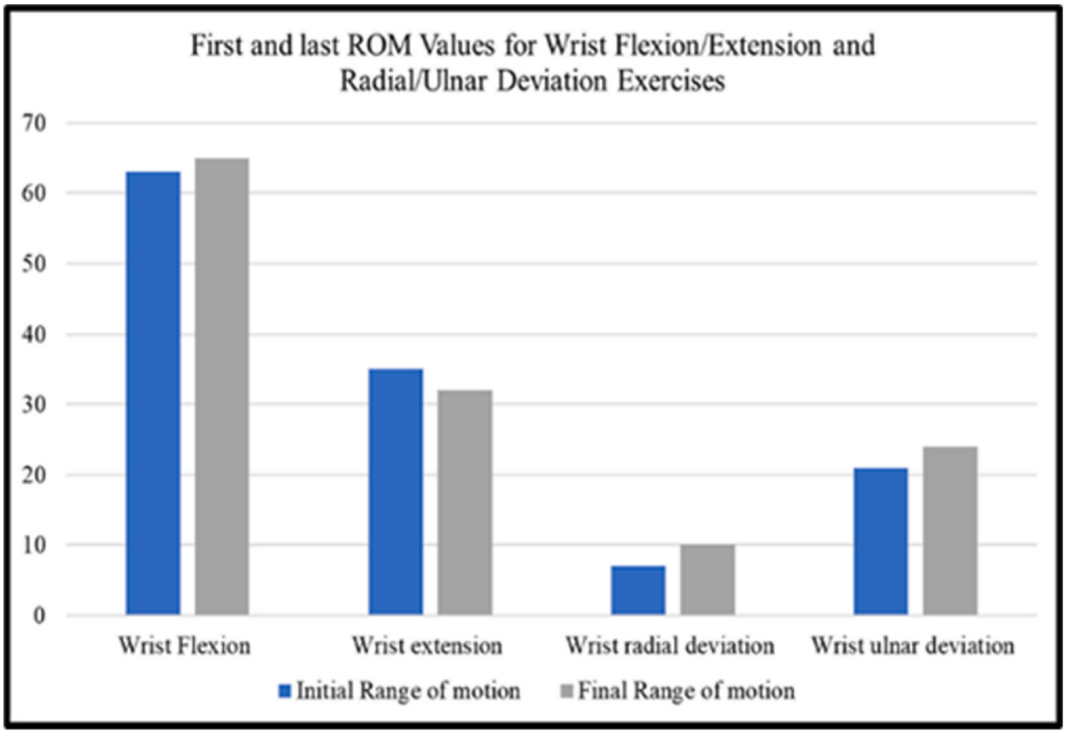

Fig. 6. First and last ROM values of the AROM full flexion exercise.

Table 2
Fugl meyer assessment of the upper extremity at T0, T1, and T2.

- *Jebsen-Taylor Hand Function Test:* As displayed in Table 3, 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.

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

Table 3
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

single-case study, we aimed to evaluate a hand telerehabilitation intervention 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 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 the range of motion and 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 project [26]. This was demonstrated by the consistent adherence to the intervention for about 100 min per week. Hand function also improved throughout 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 [27]. 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 [28]. 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 [29]. 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 [30].

Our participant consistently adhered to the proposed 8-week home-based intervention, completing all the assigned 40 sessions, each lasting an average of 20 min. Thus, the exercise duration totalled approximately 800 min or about 100 min per week (20 min 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 [31–33]. The provision of shorter therapy durations, such as 20 min, has been shown to enhance accessibility and reduce the sense of overwhelm in telerehabilitation [34]. 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-min 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 min pertain solely to the actual training time, excluding activities such as the donning and doffing of the smart glove or calibration procedures. These findings enhance our understanding of the flexibility in telerehabilitation interventions, offering insights for future research and clinical practice. Our user-centred approach aimed to make therapy more accessible by removing specific training time restrictions and integrating it seamlessly into daily life. Prioritizing shorter, manageable sessions, this approach resonated with participants and caregivers, adapting therapy to daily routines, and reducing burdens. The observed heightened mobility potentially influenced the participant's perception of substantial improvement, fostering commitment to the therapeutic journey and sustained adherence [35].

Innovation-wise, we introduced a unique approach to monitor the changes in ROM in both clinical settings and/or at home. Our data showed a noticeable improvement in the ROM across all fingers, indicating the effectiveness of the intervention. Tangible 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 [36]. Given the crucial role of the thumb in activities such as writing and object manipulation [37, 38], even a slight improvement in its ROM can have a tangible 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 [39]. 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 [40]. 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 [41]. 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 [41] 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 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 min weekly. In our study, we observed comparable results, with a usability score of 77.5 % and an average training duration of 100 min 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) [42] 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 [42]. 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 to record the research outcome measures and allowed them to choose their 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 5 h 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 [26]. 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 [43,44]. 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.

5. Limitations

The results presented in this study are preliminary since based on a single-case study. The study focuses on a single participant with mild upper extremity dysfunction, which may not represent the broader stroke survivor population. We did not thoroughly explore fatigue and emotional stress which should be added as potential adverse effects in future research. We recommend conducting a large-scale study before any generalization is made about the effectiveness of the iManus as a new rehabilitation technology or the clinical efficacy of the platform. In such a study, we suggest comparing the two modalities of intervention: telerehabilitation as we proceeded in our study versus conventional therapy at an outpatient clinic. Future research should also focus on the long-term effects of the proposed intervention. Also, our study did not explore the real-life logistics and resources, and the cost-effectiveness of the proposed telerehabilitation approaches. Intuitively, the proposed intervention would reduce travel costs, minimize family members' absence from work, and decrease miscellaneous travel-related expenses.

6. Conclusion

In this study, we evaluated the feasibility, safety and clinical efficacy of a hand telerehabilitation intervention. The results we gathered suggest that patients with mild symptoms post-stroke 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 score on the System Usability Scale, 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.

CRediT authorship contribution statement

Jasem Banihani: Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis. **Mohamed-Amine Choukou:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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