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Could an integrated VR-based telerehabilitation platform to support RECOVERY and maintenance of FUNctional abilities be usable and acceptable to older adults with neurological conditions?

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Could an integrated VR-based telerehabilitation platform to support RECOVERY and maintenance of FUNctional abilities be usable and acceptable to older adults with neurological conditions?

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Abstract

Background: With the increasing prevalence of neurological conditions among older adults, there is a growing need for effective home-based rehabilitation solutions supporting long-term functional recovery while minimizing caregiver burden. Virtual reality (VR)-based interventions have shown promising results in enhancing neuroplasticity and motivation. However, the usability and acceptability of integrated VR telerehabilitation systems in home settings remain underexplored.

Objective: This study aimed to evaluate the usability and acceptability of the RecoveryFun system, a prototype integrated VR-based telerehabilitation platform designed to support upper limb functional recovery in older adults with neurological conditions. It also investigated impact on patients' quality of life, caregiver stress, and healthcare professionals'system perception.

Methods: Patients aged over 60 years with neurological conditions and moderate upper limb function were recruited to test the system. The system comprised a VR headset with exergames, a wearable stress monitoring sensor, a caregiver mobile app and a clinician web platform. Usability and acceptability were evaluated with a 4-week pre-post study during which each participant followed an individualized rehabilitation plan of at least two weekly training sessions,supported by a caregiver. Secondary outcomes included functional ability, quality of life and interest to use the system for the patient, while perceived stress and system impact for the caregiver.

Results: Sixteen patient–caregiver pairs were enrolled across Italy, Belgium and Switzerland; fourteen completed the study, along with six professionals. Patients reported good usability and high satisfaction with the comfort and ease of use of the system. Caregivers found the system usable and not impacting their routine, with reduced stress levels and perceived benefits in patient motivation. Professionals valued remote individualized rehabilitation, noting some setup and adaptability issues.

Conclusions: RecoveryFun demonstrated good usability and acceptability across user groups. With further refinements, it could be a valuable home telerehabilitation solution for older adults with neurological conditions.

Trial Registration: ClinicalTrials.gov (NCT06640452), registered on 2024-10-10

Keywords:

older adult; telerehabilitation; virtual reality; upper limb; usability; neurorehabilitation.

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1. Introduction

Demographic ageing [3], the increasing prevalence of overweight and obesity [4],[3] the rising incidence of diabetes [5], and the overall growth of cardiovascular risk factors are expected to lead to a higher incidence of cerebrovascular diseases in Western countries over the coming decades [6–8].

Stroke, in particular, is currently one of the leading causes of disability worldwide [9], with approximately 1.5 million new cases diagnosed each year in Europe, generating an estimated annual cost of € 60 billion [10]. These data highlight the substantial economic burden on national health systems, which is likely to intensify as demographic pressures increase.

In response, the study of healthcare economics and strategies for optimizing resource allocation has become an increasingly relevant and debated topic. Stroke care is currently undergoing a transformation, driven by technological innovation and a shift towards home-based rehabilitation models. These models are recognized for their cost-effectiveness and sustainability, regardless of a country's income level [11].

At the same time, healthcare systems are under mounting pressure to contain costs while maintaining or improving the quality of care. Notably, approximately 80% of stroke survivors experience some degree of upper limb motor impairment [12], making upper limb rehabilitation a persistent and critical challenge. Functional recovery is often hindered by the phenomenon of "learned non-use", a behavioral adaptation in which patients progressively avoid using the affected limb, thereby restricting both engagement in therapy and overall progress [13].

Addressing this challenge requires interventions grounded in neuroplasticity, —the central nervous system's ability to structurally and functionally reorganize in response to injury or external stimuli—which is considered a foundational principle in post-stroke recovery. Effective neurorehabilitation depends on repetitive, intensive, and meaningful interventions that promote adaptive neural re-mapping [14, 15]. Clinical physiotherapy interventions have also been shown to improve functional ability and balance after stroke, although evidence of corresponding changes in biological markers of neuroplasticity remains less conclusive [16].

Telerehabilitation has emerged as a promising solution in this context, leveraging a variety of technologies such as immersive and non-immersive Virtual Reality (VR) systems, serious gaming applications, motion-tracking sensors, robotic devices, active gloves, and biofeedback platforms. These tools have been shown to enhance patient adherence, motivation, and therapy efficacy, while enabling remote clinical monitoring [17–19]. VR, in particular, has gained traction in neurological rehabilitation due to its ability to deliver task-oriented, repetitive training that stimulates the production of Brain-Derived Neurotrophic Factor —a key molecule involved in synaptic plasticity, neurogenesis, and cortical reorganization after stroke [20–22]. Numerous studies have demonstrated the effectiveness of VR in treating patients with neurological impairments. Its application extends to a wide range of neurological disorders with varying etiologies, including vascular, neurodegenerative, autoimmune, and genetic conditions [23, 24].

By creating enriched, multi-sensory environments, VR fosters engagement and motivation, facilitating neural reorganization and motor recovery [25, 21]. Task-specific, VR-based interventions have been shown to counteract

learned non-use and promote functional gains. The use of VR has an effect in the structure of brain: improved interhemispheric balance, enhanced connectivity between different functional areas, increased cortical representation mapping of the affected limb muscles, improved neural plasticity measures were correlated to enhanced behaviour outcomes, increased activation of regions in the frontal cortex and the mirror neuron system may be involved in VR interventions [25]. Numerous randomized controlled trials and meta-analyses support VR's efficacy in improving motor function, range of motion, muscle strength, and overall quality of life in stroke survivors [14].

Within this framework, the RecoveryFun project—an inclusive telerehabilitation initiative for ageing well in the new decade—was developed under the European Active Assisted Living (AAL) Programme. The project aimed to design, test, and commercialize an innovative digital platform for personalized, home-based telerehabilitation. The prototype system integrates immersive VR, Internet of Things connectivity, and Artificial Intelligence technologies to support upper limb rehabilitation in older adults with impairment [2].

At the outset, project partners collaboratively defined the rehabilitation framework and developed the clinical study protocol [26].

The *RecoveryFun* system was conceived to reduce healthcare pressure and costs, while ensuring continuity and quality of care. This system is intended to support upper limb rehabilitation at home and alleviate caregiver burden, enabling more efficient resource utilization and promoting long-term functional recovery.

A key aspect that must be considered when analyzing the RecoveryFun prototype system is the innovation of the system. In fact, numerous studies have investigated the use of VR in both clinical and domestic settings [27, 21, 28, 29]. However, the independent use of immersive VR at home by patients, remotely monitored by therapists via a dedicated platform with innovative, state-of-the-art features, is novel and requires initial investigation of the prototype at this stage.

The usability and acceptability of the system are two fundamental aspects for achieving therapeutic goals. A well-designed system that is accessible and user-friendly promotes adherence to treatment and allows for regular and continuous use, which are crucial elements for stimulating neuroplasticity and improving motor functions [30]. The successful use of rehabilitation technologies depends on factors related to user experience, such as the intuitiveness of the interface, ease of use, and the sense of presence that the technology is able to generate [30].

To assess the system's usability and acceptability in an unsupervised, home-based setting, the research team conducted a dedicated study. While existing literature strongly supports the use of VR in hospital-based neurorehabilitation [14], fewer studies have explored its application in fully autonomous home environments. This study aims to evaluate the usability and acceptability of a prototype home-based telerehabilitation system designed for older adults, operated without direct professional assistance, to explore its perceived benefits and potential to advance neurorehabilitation.

2. Methods

The study is designed as a usability and acceptability study to test the RecoveryFun prototype system. The entire protocol, including the description of the system components, exergames, inclusion and exclusion criteria, scales and procedures has been previously described in detail [26]. Therefore, in the next few paragraphs we provide concise methodology summaries to facilitate the reading and comprehension of the paper.

2.1 The RecoveryFun prototype system

The RecoveryFun prototype system is designed for upper limb motor through a set of seven VR exergames for training purposes. For each exergame, the motion parameters are set on the basis of the measurements evaluated in the calibration phase during a first session with the physiotherapist.

The system is composed of a series of integrated components. In particular, the patient is provided with:

- A virtual reality headset (PICO 4 VR headset) (Figure 1) with the exergames VR application (Figure 2), to perform his/her training session;,
- A wearable sensor (Shimmer very pulse) (Figure 1), connecting to the network through a gateway, to measure Photoplethysmography and Galvanic Skin Response data, which are then processed by an appropriate algorithm to derive measures of stress and fatigue for the clinicians;
- A tablet, to have remote support by the clinical staff;
- A router, to provide the internet connection.

Figure 1. Selected components of the RecoveryFun telerehabilitation prototype system: VR Headset (Pico 4) and a wearable sensor (Shimmer very pulse)

Figure 2. Exergames VR application

The carer has the possibility to use the tablet during the patient's clinical session to visualize the VR environment in which he/she is playing and has access to the secured mobile caregiver app installed on his/her smartphone. In brief, the caregiver app gives the possibility to the caregiver to motivate and support the end user in the therapy adherence, by sending motivational messages visible to the patient in the RecoveryFun VR application's home. Moreover, through the dedicated application, the caregiver is able to monitor the training adherence of the patient and consult support material on the use of the system (explanatory videos and FAQ section) to help the patient in using the devices, acting as a 1st level assistance. The carer also has the possibility to use the tablet during the patient's clinical session to visualize the VR environment in which he/she is playing.

The professionals (physiotherapist and management staff) rely on the clinical platform, a secured web app, to manage the clinical session settings and to monitor the patient's data. In the clinical platform an authorized clinician can:

- Edit the clinical/administrative data of the assigned patients;
- Manage the VR devices and assign them to a specific patient;
- Associate the caregiver with the correspondent patient;
- Create rehabilitation plans for specific patients;
- Monitor the activity of the patients (i.e., observe the progress of the rehabilitation sessions executed, see the number and the duration of training sessions executed, evaluating compliance to the rehabilitation plan);
- Connect to a secured video channel to see the patient's activities in the VR environment.

2.2 Intervention

The study was conducted using a pre-post approach, with a group of patients and carers receiving the system and undergoing data collection before and after the installation and use of the technical solution. In particular, the study involved four main phases: recruitment and baseline evaluation; followed by education sessions for patients and caregivers; home installation and use of the rehabilitation system with caregiver support; weekly remote monitoring by clinicians; and a final evaluation after four weeks to assess usability, acceptability, and overall impact. Three centres of recruitment were involved: IRCCS INRCA (Italy), TRAINM (Belgium) and ZURZACH Care (Switzerland). As defined in the protocol, a total of 30 participants (15 patients and 15 informal caregivers) were to take part in the trial. The study lasted 4 weeks, during which each participant completed an exemplary, individual rehabilitation plan with at least two rehabilitation sessions of at least 10 minutes and at most 30 minutes per week. Each rehabilitation session was planned and scheduled by the therapist remotely via the dedicated clinical platform. The physiotherapist, by monitoring performance and adherence data regarding previous sessions through clinical platform and (video)calling patients when necessary, was able to create sessions customized to

the patient by choosing the most useful level and exergames according to the rehabilitation goals. The patient could still perform more sessions if desired.

2.3 Study population

The population selected for the trial in the RecoveryFun project consisted of patients aged over 60 years who had overcome an acute neurological event (e.g., stroke or brain injury) no more than 12 months before the recruitment time and completed intensive inpatient rehabilitation. The patients we were referring to had already returned home and needed to maintain the goals achieved or increase functionality. In order for the patient to be able to use the system properly (to date), specific physical/cognitive requirements were needed. Patients must have sufficient physical function, including a Trunk Impairment Scale (TIS) [31] score of at least 20, a Fugl-Meyer Assessment (FMA) [32] score of 33 or higher for upper limb motor function (with specific abilities in shoulder, elbow, wrist, and hand movements), and the ability to sit unsupported for at least 30 minutes without fatigue. Adequate shoulder range of motion and good trunk control were essential. Cognitive ability was also required, with a Montreal Cognitive Assessment (MoCA) [33] score of 24 or above. Additionally, patients must have a caregiver available to assist if needed. Exclusion criteria included any condition that would prevent safe or effective use of a VR headset, such as certain visual disorders, implanted medical devices, epilepsy, vertigo, severe fatigue, psychotic disorders, or cognitive impairment (MoCA <24). Patients must also be capable of providing informed consent and wearing the VR headset either independently or with minimal help.

2.4 Outcomes

The study aimed to assess the usability and acceptability of the RecoveryFun prototype system. The study was structured into three phases: recruitment (R), baseline evaluation (T0) and final evaluation (T1). A set of tools was used for each phase in order to evaluate the study outcomes.

In particular, primary outcomes investigated in the study were:

1. Usability perceived by the patient through System Usability Scale (SUS) [34] (T1) and User Experience Questionnaire (UEQ) [35] (T1);
2. Usability perceived by the informal caregiver through SUS (T1);
3. Acceptance perceived by the patient through Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) 2.0 [36] (T1).

In addition, secondary outcomes of the study were:

1. Impact of the system on patient quality of life, measured with the World Health Organization Quality of Life Bref (WHOQOL-BREF) [37][4] (T0 and T1), and functional ability with the FMA (R and T1);
2. Stress perceived by the caregiver thought Perceived Stress Scale (PSS) [38] (T0 and T1) and an ad-hoc questionnaire (T1);
3. Patient interest to use and the attitude to pay using an ad hoc questionnaire (T1).
4. Impact of the system on the caregiver to understand whether it is a helpful and supportive tool or causes additional difficulty through an ad hoc questionnaire (T1) and on the professionals to evaluate the overall experience with the system, its usability, possible benefits and critical issues through a focus group or individual interviews (T1).

The protocol also included study specific questions on demographics and attitudes to technology from both the patient and informal caregiver (T0). In addition, subjective health and social support were explored with the patient with an ad hoc questionnaire (T0).

2.5 Statistical analysis

The first step of the data analysis involved the description of the sample. Continuous variables were reported as either mean and standard deviation or median and interquartile range on the basis of their distribution (assessed using Kolmogorov-Smirnov test). Categorical variables were expressed as absolute numbers and percentages. The trial comparison between pre- and post- conditions was evaluated by paired t test (for normal distribution), Mann-Whitney U tests (for non-normal distribution), or Chi-Square tests (for categorical variables). *p*-values below 0.05 were considered statistically significant; however, due to the limited sample size, no results reached this threshold. Considering the exploratory nature of the analysis, exact p-values were not reported in the text. Moreover, a linear regression model on the outcome variation between baseline and follow-up was estimated in order to evaluate measure variation.

3. Results

3.1 Samples

The study involved a total of 14 patients, 14 caregivers and 6 healthcare professionals, whose descriptions will be presented below (see Supplementary file 1 and 2). Initially, 16 patients were enrolled;however, two participants in Belgium withdrew due to a general decline in their physical health, unrelated to the study. Accordingly, the number was reduced by two caregivers. Moreover, in Switzerland at T1 the Fugl-Meyer was not re-administered. Therefore, at T1, data will be reported for a sample of 8 patients for functional ability, following the exclusion of one participant identified as an outlier.

3.1.1. Patients

The sample was composed of 14 patients among Italy (50%), Belgium (14.3%) and Switzerland (35.7%). Participants were eight (57.1%) males and six (42.9%) females with an average age of 73.2 years. Specifically, three people (21.4%) were under 65, four (28.6%) were between 66 and 75, six (42.9%) were between 76 and 85, and only one person (7.1%) was over 86. Half of the sample (50%) was married, while the other half consisted of three people (21.4%) who were widowed, two (14.3%) in a full time relationship, one (7.1%) separated and one (7.1%) single. The majority (50%) had secondary education, while four participants (28.6%) had tertiary education, two (14.3%) primary and one person (7.1%) no education.

As mentioned in the methodology, recruitment tools were used, whose mean values are reported below: Fugl-Meyer 52.36 (SD=12.02), TIS 21.36 (SD=1.22) and MoCA 26.21 (SD=2.08). Considering sex differences, on average, females scored higher on the Fugl-Meyer than males. Instead, regarding patients' age, people over 75 years of age had a lower average score on the Fugl-Meyer physical assessment and on the cognitive assessment than people under 75 years of age. No further differences emerged.

The data collected through the Matching Person and Technology – Survey of Technology Use -Consumer (MPT SOTU-C) revealed that the technologies most frequently used by participants were: computer (11 people), smartphone (6 people), mobile phone (7 people), smart banking, smart tv and tablet (2 people each), tv (2 people), car technology and smart blood pressure monitor (1 person each). Moreover, the mode of response most commonly used was positive (M= 17.07, SD= 5.69), followed by neutral (M= 10.64, SD= 4.36) and negative (M= 3.29, SD= 3.10). Females, compared with males, reported fewer positive and more neutral and negative responses. In contrast, people older than 75 years provided more negative responses and less neutral than those younger.

3.1.2. Caregivers

The sample was composed of 14 caregivers among Italy (50%), Belgium (14.3%) and Switzerland (35.7%). Participants were eleven (78.6%%) females and three (21.4%) males with an average age of 62 years. Specifically, most caregivers (57.1%) were under 65 years of age, 35.7% were between 66 and 75 years old and 7.1% between 76 and 85 years old. Six people (42.9%) were married, three (21.4%) were in a full-time relationship, two (14.3%)

single, one (7.1%) widowed and one (7.1%) divorced. One (6.2%) refused to answer. Most of them (42.9%) had secondary education, while five participants (35.7%) had tertiary education and three (21.4%) primary. Half of the sample (50%) was retired, four (28.6%) were still working full-time, two (14.3%) were working part-time and another (7.1%) was working inside the home. Most of the caregivers (57.1%) involved were the patient's spouse/partner. In other cases, the patient was their parentv (28.6%), grandmother (7.1%) or friend (7.1%).

Considering data collected through MPT SOTU-C, technologies most frequently used by caregivers were: smartphone (9 people), computer (7 people), smart tv and tablet (4 people each), credit card (4 people), smart banking (2 people) and car technology (2 people). In addition, the mode of response most commonly used was positive (M= 19.50, SD= 3.70), followed by neutral (M= 8.50, SD= 4.38) and negative (M= 3.00, SD= 3.62). Taking sex into consideration, both sex gave predominantly positive responses. The difference emerged in the other response modes: while males tended to use more negative responses, females neutral. Instead, in relation to age, the frequency of neutral and negative responses was on average higher, while that of positive responses was lower in people under 65 than in those who were older.

3.1.3. Healthcare professionals

Six healthcare professionals among Italy (33.3%), Belgium (33.3%) and Switzerland (33.3%) were involved. Participants were five (83.3%) males and one (16.7%) female with an average age of 33 years. All (100%) had tertiary education, three (50%) in physiotherapy, two (33.3%) in science and one (16.7%) in psychology. Most of them (83.3%) had good familiarity with technology and one (16.7%) excellent. All of them (100%) had past experience with virtual reality.

3.2. Primary outcomes

3.2.1. Usability perceived by patients

The average score of SUS was 68.57 (SD= 18.42) in which 100 is the maximum and 68 is the threshold for a usable system [39]. Therefore, the system appeared to have good usability from the perspective of the patients. The average SUS scores revealed that male expressed a slightly higher level of system usability in comparison with females. More significant differences emerged when considering the age of the patients. In fact, those over 75 years old reported greater usability of the system than those under 75 years old.

In addition, examining the data collected through UEQ, it was found that patients rated the RecoveryFun system positively for all scales. Specifically, the average scores for the different scales are as follows: Novelty 1.73 (SD= 1.21), Attractiveness 1.70 (SD= 1.05), Perspicuity 1.52 (SD= 1.44), Dependability 1.36 (SD= 0.95), Stimulation 1.36 (SD= 1.56) and Efficiency 1.12 (SD= 1.09). Moreover, the dimension of pragmatic quality aspects obtained from patients an average score of 1.33 (SD= 1.08) and the hedonic quality aspects of 1.54 (SD= 1.32). On average, females scored higher than males on hedonic quality aspects, while individuals over the age of 75 scored higher than younger individuals on both hedonic and pragmatic quality aspects.

Considering the various tools used, SUS scores showed a strong correlation with pragmatic quality aspects (r= 0.866) and a moderate correlation with hedonic quality aspects (r=0.410). In addition, SUS scores also correlated with QUEST scores, more for those inherent to the headset (r= 0.675) than the wearable sensor (r= 0.383).

3.2.2. Usability perceived by informal caregivers

The SUS revealed that caregivers on average rated usability as good (M=71.25; SD=19.68), with highest scores reported by male than female and by people under 65 years old rather than over.

3.2.3. Acceptance perceived by patients

Regarding the users' satisfaction with the system measured by QUEST, both the headset and sensor scores were above 4 showing high satisfaction with these technologies. Specifically, the average score obtained by the headset

was 4.31 (SD= 0.59) and by the sensor was 4.59 (SD= 0.27). No significant differences were found in QUEST scores in relation to patient sex and age, except for slightly higher scores in the headset rating in people over 75 years of age compared to younger people.

Moreover, dimensions considered most important by the patients for both the headset and the wearable sensor were easy to use, adjustments and weight. One patient didn't express preferences for wearable sensor dimensions.

3.3. Secondary outcomes

3.3.1. Impact of the system on patients quality of life and functional ability

In exploring the perceived benefits of the system on patients, at both the baseline and final evaluation, WHOQOL-BREF was administered to collect information on quality of life, specifically in physical health, psychological, social relationships and environment. The scores at baseline for each dimension were as follows: physical health (M=62.29, SD=9.82), psychological (M=64.88, SD=11.41), social relationships (M=71.43, SD=11.65) and environment (M=74.33, SD=12.02). Thus, the sample reported higher levels in the domains of environment and social relationships than in the domains of physical health and psychological. In all WHOQOL-BREF domains, mean scores in males were higher than in females, while, with regard to age, people older than 75 years had higher mean scores in the physical and psychological health domains, while those younger than 75 years old in the environment domain. The mean scores of social relationships, however, on average were not significantly different.

Instead, at the final evaluation, on the one hand positive variation in physical health (M=1.22, SD= 2.02) and psychological domain (M=0.81, SD= 2.34) was observed and on the other negative variation in social relationships (M=-0.24, SD=2.85) and environment (M=-0.70, SD=2.94). Considering sex, females in the environment domain tended to show a greater decrease than males. In the social relationships domain, however, men showed a slight decrease and females a small increase. With regard to age, people over 75 presented higher change scores over time in all domains compared to those under 75.

In order to better characterize the patients and investigate potential changes in motor function, Fugl-Meyer was administered also at the final evaluation. At the end of 4 weeks, there was a positive variation of 1.11 (SD= 17.04) in the Fugl-Meyer scores. Changes over time on average were greater in males than in females and in people older than 75 than in those younger. One of the participants during the trial had pneumonia affecting her functional ability. If the pre-post difference is calculated excluding this participant the positive variation is 6.25 with a standard deviation of 7.76.

3.3.2. Stress perceived by caregivers

Caregivers through PSS showed a reduction in perceived stress of 2.86 (SD: 3.32). This reduction appeared greater in females than in males and in people older than 65 than in those younger ages.

The increase in PSS over time was then analysed in relation to mean scores of caregiver outcome variables (SUS and MPT SOTU-C). Regarding usability, participants who experienced an increase in perceived stress reported a lower SUS score (M= 51.25, SD= 15.91 vs M=) compared to those who did not, who reported a higher SUS score (M= 74.58, SD= 18.70). Instead, regarding MPT SOTU-C, people who perceived increased stress used more a negative response mode (M= 8.00, SD= 8.49) than patients (M= 2.17, SD= 1.90) who did not report an increase in stress. The opposite occurred for neutral responses: those who perceived an increase in stress used fewer neutral responses on average (M=3.00, SD=4.24) than people who did not report such an increase (M=9.42, SD=3.82).

To further explore this dimension at the final evaluation, some ad hoc qualitative questions were also administered. They revealed that the majority of caregivers (92.9%) did not change the daily routine after the system was introduced. Some reported appreciations about it ("*The system has not modified my daily routine. In my opinion is useful that there isn't a scheduled program*" – ID07ITA) and strategies used ("*Within the day I carved out 15*

minutes to manage the session" – ID13ITA; "*I had scheduled her timetable with my timetable*" – ID17ITA). One caregiver (7.1%), on the other hand, reported that she changed her routine, although mostly at the beginning ("*In the beginning needed more time, to get used to the system*" ID13CHE).

Regarding how the system was accepted by their family members, the majority of caregivers (78.6%) indicated that it was positively accepted. Some comments expressed by caregivers were: "*My mother has accepted very well the system*" (ID07ITA); "*With interest*" (ID09ITA); "*Very positive and proactive*" (ID13ITA); "*Serenely*" (ID15ITA); "*Naturally*" (ID19ITA); "*Good*" (ID09CHE); "*Surprisingly good, although he was initially annoyed by the games because of the poor hand-tracking*" (ID13CHE); "*Good, she was very motivated*" (ID15CHE). In contrast, a minority (21.4%) reported difficulty in the acceptance of such technology by the patient ("*Initially fine. Then showed reluctance to do sessions due to hand pain*" - ID11ITA; "*It was not really suitable to his condition and as he is sceptic*" - ID02BEL).

Finally, most caregivers (64.3%) believed that the system has improved patient self-management of rehabilitation ("*In my opinion the system helps the rehabilitation*" – ID17ITA). On the contrary, a minority (21.4%) reported that, according to them, the system made no improvements and others (14.3%) that they could not answer ("*time was too short to be able to assess this*" ID15CHE).

3.3.3. Patients' interest in using the system and attitude toward paying

The majority of patients considered the system to have been extremely (35.7%), fairly (28.6%) and slightly (21.4%) useful/helpful. In contrast, a minority (14.3%) said the system was not helpful at all.

Patients reported that factors influencing their decision to use a home rehabilitation system included the possibility to try out the device themselves (28.6%) or receiving a recommendation from their physician or another trusted healthcare worker (28.6%). Other aspects mentioned were seeing someone demonstrate the device's use (21.4%), receiving a recommendation from a friend or family member (7.14%), or having the opportunity to try and receive a demonstration during rehabilitation (14.3%). Two patients (14.3%) were unsure how to respond.

Finally, the following list presents in order of decreasing significance the factors deemed most important by patients when thinking about whether or not to use a home rehabilitation system:

- Recommendation from my physician (M=4.86, SD=0.36);
- Ease of use (M=4.64, SD=0.63);
- How much support I receive from caregivers (M=4.43, SD=0.94);
- State of my health (M=4.43, SD=0.94);
- Cost (M=4.21, SD=0.8);
- Whether insurance scheme will pay for part or all of the cost (M=4.21, SD=0.8);
- Perceived value (M=3.79, SD=0.97);
- Level of comfort with technology (M=3.71, SD=1.33);
- Easy to buy/availability (M=3.57, SD=0.94).

Instead, the aesthetic appearance of the device was rated on average as not important (M=2.29, SD=1.2).

3.3.4. Impact of the system on caregivers and professionals

Caregivers' responses to the questionnaire on the impact of the system revealed that most of them (35.7%) never used the caregiver app. The remaining study participants used it rarely (28.6%), sometimes (28.6%) or quite frequently (7.1%).

The caregiver application in the relative's home rehabilitation for most participants was not important (28.6%) or somewhat unimportant (21.4%). Instead, 35.7% of caregivers believed the application was important, somewhat (28.6%) or very (7.1%). A minority (21.4%) expressed a neutral opinion about the caregiver application.

Moreover, most caregivers (92.9%) stated that the system for the person they were assisting was useful/helpful. Specifically, 50% considered it fairly, 28.6% only slightly and 14.3% extremely useful/helpful. Only one caregiver (7.1%) said the system was not useful at all.

Considering the supporting role played during the rehabilitation process, all caregivers (92.9%), except one (7.1%), reported that the use of the system was not an additional burden. Some comments expressed by caregivers were: "*No, I didn't feel a heavy load*" (ID07ITA); "*I do not see it as an additional burden; it is a time when I lend my help, as the time frame is also reduced*" (ID13ITA); "*No additional burden, but attention to a friend*" (ID15ITA); *"No burdens were relieved, although he was honoured to be in the project and gave him a sense of importance*" (ID02BEL); "*It relieved me*" (ID11CHE). The participant who, on the contrary, reported an additional burden given by the use of the system attributed it to the "*time required*" (ID13CHE).

Most caregivers (71.4%) agreed on integrating classical rehabilitation with home telerehabilitation systems such as RecoveryFun. Some comments expressed by caregivers were: "*They are different type of rehabilitation and both are useful, are complementary*" (ID07ITA); "*telerehabilitation is a way to make rehabilitation more interactive, so I agre*e in integration" (ID13ITA); "*prefer to integrate, because it is also for me a variation*" (ID07CHE); "integration, because independent of *time and place*" (ID11CHE). In contrast, a minority (21.4%) reported that they would prefer classical rehabilitation because of the clinician's presence next to them or the "*social contacts*" (ID13CHE). One (7.1%) expressed a dubious opinion ("*depending on the effort (distance to therapy, place of living)*" ID15CHE).

In the current situation where telerehabilitation is only partially reimbursed, most caregivers (85.7%) thought it could be valuable to pay for the use of the RecoveryFun system. Those who agreed to pay to utilize this service considered it reasonable to pay monthly 50-100€ (42.9%), 100-150€ (14.3%) or 150-200€ (7.1%). Three caregivers (21.4%) refused to answer and two (14.3%) didn't know what to reply.

Caregivers, except for one who did not reply, used the following words to list the positive aspects of the system: fun; cognitive; stimulating; independently; relaxing; little time; together; innovative; useful; additional; creative; no travel; helps; various; followup.

Instead, negative aspects reported were as follows: few games; complicated; screen not centered; too difficult; not suitable for rehabilitation; not autonomously; not customizable; wifi; less personal contact; not clinician; user friendliness. Only 9 caregivers (64.3%) responded as 5 (35.7%) did not report any negative aspects.

Finally, healthcare professionals provided their feedback on the various components of the system. The critical issues sometimes found in the use of virtual reality that hindered the execution of games were: virtual screen distance too close, screen angle not centered, interaction with objects not always working properly. Instead, the sensor charging mode appeared cumbersome. Regarding the clinical platform, it was found to be easy to use. Professionals have, in addition, proposed to improve it through the input of both sensor and caregiver app data and the history and duration of previously scheduled rehabilitation sessions.

Considering patients, system setup at home should be further simplified as the system has too many components and, if the patient or caregiver is unfamiliar with the technology, it can be complex. In addition, exergames should be more adaptable to the patient's abilities through a wider range of games and levels in which the therapeutic purpose is clearly described. Gamification could also be expanded, for example by giving a score at the end of the game or the opportunity to obtain prizes.

Conducting the trial emphasized the importance of caregiver involvement and offered the opportunity to observe the benefits of a system such as RecoveryFun for patients. In fact, healthcare professionals mentioned a positive impact of the system on patients, also related to the fact that they were autonomous in the mode and timing of performing the exergames and that the rehabilitation sessions seemed to improve both motor and cognitive status. Indeed, the possibility of doing as many exercises as patients with a neurological disease wish is favorable, as the chances of faster recovery are increased.

Finally, healthcare professionals invited for future studies to consider that selecting a specific population to have more comparable data limited the possibility of involving more participants. Based on their experience during the trial, they suggested patients with chronic conditions and orthopedic disabilities are likely to be the best targets for the solution.

4. Discussion

4.1. Principal findings

The goal of this study was to assess the usability and acceptability of the RecoveryFun prototype system in telerehabilitation. Starting with patients' experience, they reported good usability of the system, as evidenced by an average SUS score above the acceptability threshold. The UEQ also revealed positive impressions on all dimensions, particularly in terms of novelty and stimulation. Patients expressed high satisfaction for the headset and wearable sensor, emphasizing ease of use and comfort. Notably, most patients found the system useful and expressed interest in using similar solutions in the future, especially if recommended by a physician. Satisfaction with both the headset and wearable sensor was high (QUEST >4), emphasizing comfort and ease of use as decisive features. The results obtained from the SUS, QUEST, and UEQ scales consistently indicated good usability of the RecoveryFun system across all its components. In particular, the highest scores were reported for the wearable sensor on the QUEST and for the novelty and attractiveness dimensions on the UEQ, reflecting positive user perceptions of comfort, ease of use, and engagement. Similarly, SUS scores exceeded the threshold for acceptable usability, further supporting the system's feasibility. Taken together, these findings suggest that RecoveryFun has great potential for autonomous use at home by patients aged over 60 years with limited technological familiarity.

Caregivers also rated the system as usable and manageable within their routine. Importantly, almost all caregivers reported that support for use of the system was not changing their routine, a potential critical factor for sustainable implementation in the home environment. Although caregiver use of the application was relatively limited, those who used it recognized its motivational potential. However, the assessment of the application's use could be subject to cultural bias, as in Italy it is very common for the caregiver to live with the patient. For this reason, the use of the system may be less motivated, in contrast to other contexts where the patient does not live with the caregiver. The system was also perceived as making a positive contribution to the rehabilitation pathway, with several caregivers noting increased patient motivation and emotional involvement. A reduction in perceived stress (as measured by PSS) among caregivers was also documented, particularly among women and older participants.

These results are consistent with current evidence [40] which have repeatedly reported that immersive VR and exergames-based interventions are feasible, well-tolerated, and often preferred by older adults compared to conventional rehabilitation modalities. In particular, the SUS score observed in this cohort, aligns with analogous studies involving technology-assisted home rehabilitation for older adults [41].

In addition, the system may significantly alleviate caregiver burden. The availability of an immersive and motivating home-based rehabilitation program reduces the need for frequent travel to clinical centers, often a source of logistical and emotional strain for both patients and their families. Importantly, this aspect could be particularly beneficial for people living in rural or underserved areas, where access to specialized rehabilitation services is limited and transportation may represent a considerable barrier. By decentralizing rehabilitation and making it accessible at home, RecoveryFun addresses an important equity gap in healthcare provision [42].

A further innovative element of RecoveryFun is its calibration phase, which not only ensures that exergames are tailored to the patient's functional abilities but could also serve as a valuable tool for remote follow-up. Through periodic recalibration sessions performed at home, clinicians could obtain updated and objective data on motor performance, enabling them to identify with precision which patients require additional follow-up or intensified rehabilitation. This feature could transform calibration into a dual-purpose component: personalization of therapy and remote monitoring of clinical progress.

Importantly, improvements in upper limb function and quality of life as well as reductions in caregiver stress, mirror the outcomes observed in similar investigations and meta-analyses. For example, exergames and VR protocols, especially when home-based and supported by remote feedback, are linked to functional improvements, increased autonomy, and high patient satisfaction [43]. Remarkably, the reduction in caregiver perceived stress, together with the observation that the intervention did not increase caregiver burden, is a significant relief for caregivers and is echoed in other studies focusing on digital and home-based rehabilitation programs [42].

Another relevant aspect to consider is the potential impact of a system like RecoveryFun on healthcare costs and caregiver workload. From the current state of the art, it is clear that telerehabilitation represents an important opportunity to reduce healthcare costs while maintaining, or even improving, the quality of care. Moreover, it contributes to lowering the workload of healthcare professionals and caregivers, particularly for patients living in rural or underserved areas who often face logistical and financial barriers to accessing rehabilitation services [44]. However, a reliable cost–benefit or workload analysis would require larger-scale studies and more detailed economic data, some important reflections can be drawn. Conventional rehabilitation pathways are often constrained by the availability of therapists, limited treatment slots, and the economic sustainability of national healthcare systems. RecoveryFun, by contrast, offers patients the possibility to continue an engaging rehabilitation program without temporal restrictions and with minimal need for in-person supervision. This flexibility not only enhances continuity of care but may also optimize resource allocation by reducing the frequency of outpatient visits and hospital-based sessions.

Taken together, these considerations suggest that RecoveryFun could represent a cost-efficient and sustainable addition to existing rehabilitation services, particularly when integrated into hybrid care pathways that combine in-clinic sessions with home-based use. With further validation and economic analysis, such a system could become a valuable tool not only for improving patient outcomes and autonomy, but also for relieving pressure on healthcare professionals and reducing indirect costs associated with long-term disability management.

Overall, these results indicate that the RecoveryFun prototype system is a promising and generally well-accepted solution that facilitates home rehabilitation.

4.2. Strengths and limitations

The article provides a user-centred approach, involving patients, informal caregivers and healthcare professionals as active participants. Each group contributed valuable insights into the usability, acceptability and perceived impact of the system. A further strength of the study is that the RecoveryFun system was tested in a naturalistic home environment in three different European countries (Italy, Belgium and Switzerland). This ecological validity increases the applicability of the results to real-life and different healthcare contexts. Moreover, the use of both qualitative and quantitative methods maximized information gathering and understanding regarding user experience and system impact. In particular, the use of validated instruments such as SUS, QUEST, UEQ and WHOQOL-BREF strengthened the reliability of the results, while the inclusion of caregivers and health professionals provided insight into the broader care ecosystem. Furthermore, the inclusion of caregivers and the measurement of the system's impact on caregiver stress, routine and load is aligned with the latest telerehabilitation literature [42]. The literature demonstrates the excellent acceptability and usability of immersive VR systems in neurologic patients, as well as their effectiveness [14, 25, 27, 21]. However, despite the wide availability of trials on immersive VR technology in the literature, very few trials exclusively use home-based rehabilitation. For this reason, one of the strengths of the system is its innovative aspect [27, 21, 28, 29]. The results show that RecoveryFun did not increase caregiver burden and, in some cases, was perceived as helpful. This is an important aspect for the sustainability of home-based rehabilitation. The RecoveryFun prototype system represents an innovation in asynchronous telerehabilitation for the upper limb of patients with neurological conditions (e.g. stroke or brain injury). The literature reports widespread home use of semi-immersive and non-immersive VR systems like RecoveryFun. The RecoveryFun system has demonstrated good usability, and in some cases, patients were able to use it independently, requiring only minimal assistance to wear the device. This opens the opportunity to provide long-term continuous rehabilitation without increasing healthcare costs for national systems or caregivers. RecoveryFun represents a new system, and a future efficacy study are needed. In designing an RCT,

should the control group undergo the same number of sessions or follow the standard home rehabilitation program for stroke patients. The true potential of the RecoveryFun System lies in the absence of temporal, logistical, and personal limitations—while maintaining therapist supervision and treatment personalization. Finally, the proposed solution represents an integrated, multi-component system, combining VR exergames, wearable sensors for physiological monitoring, a dashboard for the health professionals and an application for the caregiver. The project reflects an interoperable ecosystem aimed at improving personalisation of therapy, motivation and remote monitoring, key attributes of modern telemedicine solutions.

Despite these strengths, key limitations of this study are the absence of a control group and the small sample size, particularly when disaggregated by outcome. Only 14 participants contributed to qualitative outcomes, and merely 9 patients were evaluable for functional parameters (FMA-UL) and among them one case was affected by an intercurrent illness. Moreover, several participants achieved very high baseline scores at T0, resulting in a ceiling effect in the data analysis. Under these conditions, any statistical testing would be prone to multiple potential biases, making the results difficult to interpret. This substantially limits the robustness of statistical analyses and the generalizability of the findings. Moreover, the short intervention period (4 weeks) does not allow conclusions about long-term adherence, functional recovery, or sustained impact on quality of life. In addition, the inclusion criteria selected patients with relatively preserved motor and cognitive function, which may reduce applicability to the wider population of stroke survivors with more severe impairments. In addition to the limitations already discussed, further aspects should be acknowledged. First, the sample was unbalanced in terms of gender distribution, with only three males compared to eleven females among the 14 participants. Second, the geographical representation, although spanning three countries, remains limited. To avoid this being a constraint, future studies should involve a broader range of European countries in order to provide a more accurate representation of the European context. Nevertheless, the observed positive trend supports the hypothesis that consistent engagement with immersive VR exergames may foster recovery, in line with the neuroplasticity principles described in the study protocol.

4.3. Future directions

Based on the limitations and the insights gathered from this field trial, several directions for future research and system development emerge. First, while this study focused on usability and acceptability, future studies should also evaluate the clinical effectiveness of the RecoveryFun system in improving motor function, cognitive function and long-term adherence to rehabilitation protocols. Randomized controlled trials with larger sample sizes and longer follow-up durations are needed to determine whether observed positive trends, such as improvements in Fugl-Meyer and quality of life scores, result in statistically and clinically significant outcomes. In addition, future research could explore the use of the system for people with mild cognitive impairment, greater motor limitations or orthopedic comorbidities, limited familiarity with the technology, or no or limited caregiver support. Regarding future development, feedback from healthcare professionals and participants revealed a need for a greater variety of games, difficulty levels and feedback mechanisms, as well as improved integration of the clinical platform with sensor and caregiver app data. It would also be desirable to reduce the number of components needed at home and the need for in-person installation. One aspect that has not been considered—but should be addressed in a future efficacy study—is the issue of healthcare costs. The discussion around this topic is complex and multifaceted. Comparing rehabilitation costs is challenging because many variables influence whether a home-based system is more or less cost-effective than in-person rehabilitation. To determine whether a telerehabilitation system is cost-effective, it is essential to stratify the population not only by clinical characteristics but also by place of residence (rural or urban areas) and living arrangements.

5. Conclusion

This study demonstrates that the *RecoveryFun* prototype system is a promising, user-centered solution for home-based telerehabilitation targeting upper limb recovery in older adults with neurological conditions. By integrating immersive virtual reality, biosensors, a video communication channel, a caregiver application, and a clinician dashboard, the system enables individualized, asynchronous rehabilitation while addressing the needs of patients, caregivers, and healthcare professionals.

Another relevant aspect to consider is the potential impact of a system like RecoveryFun on both healthcare costs and caregiver workload. However, a reliable and accurate cost–benefit or workload analysis would be difficult to perform. What can be highlighted is that RecoveryFun enables patients to continue a stimulating rehabilitation program without temporal restrictions, unlike conventional rehabilitation pathways usually limited by the resources of national healthcare services. For this reason, RecoveryFun can be regarded as a highly innovative solution in the field of asynchronous telerehabilitation with immersive virtual reality.

RecoveryFun combines several innovative features that strengthen its potential impact: the calibration phase as both a personalization and remote follow-up tool, the possibility of continuous and flexible home use, the reduction of caregiver workload, and improved accessibility for patients in rural or underserved areas. These elements position RecoveryFun as a scalable and sustainable solution that can complement conventional rehabilitation while promoting autonomy and equity of care.

High levels of usability, acceptability, and patient engagement were observed across diverse home settings. Preliminary findings suggest a positive association between system use and functional improvement, along with reduced caregiver stress and strong patient motivation. These results highlight the system's potential to extend rehabilitation beyond clinical settings while maintaining care quality and alleviating caregiver burden.

Nevertheless, limitations such as the small sample size, short intervention duration, and restricted inclusion criteria emphasize the need for further research. Future studies should focus on clinical efficacy, long-term adherence, and cost-effectiveness in larger and more diverse populations.

In summary, RecoveryFun prototype solution offers a scalable and innovative approach to home-based telerehabilitation. With continued technical refinement and rigorous clinical validation, it has the potential to become a valuable tool for promoting functional recovery and autonomy among older adults.

CRediT authorship contribution statement

Rachele Alessandra Marziali: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Benadduci:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Claudia Franceschetti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Balducci:** Formal analysis, Data curation, Methodology, Visualization. **Vera Stara:** Writing – review & editing. **Valentina Tombolesi:** Visualization, Project administration. **Sebastian Frese:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Stephan Sándor:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giovanni Renato Riccardi:** Resources, Supervision. **Elisa Casoni:** Resources, Supervision. **Valentina Di Donna:** Resources, Supervision. **Lorena Rossi:** Visualization, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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Results from the Italian study site, which represent a subset of the multicentre data presented in this manuscript, were previously published in the proceedings of the XR Salento 2025 conference [45]. The present manuscript reports the complete multicentre study population, including participants from Italy, Belgium and Switzerland.

Declarations

Ethics approval and consent to participate

The study was approved in Italy by the Territorial Ethics Committee of Marche Region (Prot. CET-M 2023 353). According to the applicable Swiss and Belgian legislation, specific ethics approval was not required for the study activities conducted in Switzerland and Belgium. The study was conducted in accordance with the Declaration of Helsinki and its later amendments. All participants and informal caregivers received comprehensive information about the study and provided written informed consent prior to participation.

Consent for publication

Not applicable.

Clinical trial registration

The study was registered with ClinicalTrials.gov (NCT06640452) on 2024-10-10

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to privacy and data protection considerations but may be available from the corresponding author on reasonable request, subject to applicable ethical and data protection requirements.

Declaration of competing interest

None declared.

Abbreviations

VR Virtual Reality

WHO World Health Organization

TIS Trunk Impairment Scale

FMA-UL Fuggl Meyer Assessment Upper Limb

MoCA Montreal Cognitive Assessment

R Recrutiment

T0 Baseline evaluation

T1 Final Evaluation

UEQ User Experience Questionnaire

SUS System Usability Scale

QUEST Quebec User Evaluation of Satisfaction with assistive Technology

WHOQOL-BREF World Health Organization Quality Of Life Bref

PSS Perceived Stress Scale

MPT SOTU-C Matching Person and Technology Survey of Technology Consumer

SD Standard Deviation

M Media

ID Identity

ITA Italia

BEL Belgium

CHE Swiss

RCT Randomized Controlled Trial

References

1. Active Assisted Living Programme. Active Assisted Living Programme. http://www.aal-europe.eu. Accessed 17 Sep 2026.

2. RecoveryFun. RecoveryFun: an integrated VR-based telerehabilitation platform to support recovery and maintenance of functional abilities among seniors. https://recoveryfun.eu/. Accessed 17 Sep 2026.

3. Kiniorska I, Brambert P, Kamińska W, Kopacz-Wyrwał I. Aging of the society: the European perspective. Bull Geogr Socio-econ Ser. 2023;60(60): 81-100. doi:10.12775/bgss-2023-0017.

4. World Health Organization Regional Office for Europe. WHO/Europe sets the course for reducing obesity in southern European countries. https://www.who.int/europe/news/item/27-06-2024-who-europe-sets-the-course-for-reducing-obesity-in-southern-european-countries. Accessed 17 Sep 2026.

5. Lascar N, Brown J, Pattison H, Barnett AH, Bailey CJ, Bellary S. Type 2 diabetes in adolescents and young adults. Lancet Diabetes Endocrinol. 2018;6(1):69–80. doi:10.1016/S2213-8587(17)30186-9.

6. Donfrancesco C, Buttari B, Marcozzi B, Sieri S, Di Lonardo A, Lo Noce C, Profumo E, Vespasiano F, Agnoli C, Vannucchi S, Silano M, Galeone D, Bellisario P, Vaia F, Palmieri L. Nutrition, Physical Activity and Smoking Habit in the Italian General Adult Population: CUORE Project Health Examination Survey 2018-2019. Healthcare (Basel). 2024;12(4):475. doi:10.3390/healthcare12040475.

7. Rajati F, Rajati M, Rasulehvandi R, Kazeminia M. Prevalence of stroke in the elderly: A systematic review and meta-analysis. Interdiscip Neurosurg. 2023;32:101746. doi:10.1016/j.inat.2023.101746.

8. Wafa HA, Wolfe CDA, Emmett E, Roth GA, Johnson CO, Wang Y. Burden of Stroke in Europe: Thirty-Year Projections of Incidence, Prevalence, Deaths, and Disability-Adjusted Life Years. Stroke. 2020;51(8):2418–2427. doi:10.1161/STROKEAHA.120.029606.

9. Roth GA, Mensah GA, Johnson CO, et al. Global burden of cardiovascular diseases and risk factors, 1990–2019: update from the GBD 2019 Study. J Am Coll Cardiol. 2020;76(25):2982–3021. doi:10.1016/j.jacc.2020.11.010.

10. Luengo-Fernandez R, Violato M, Candio P, Leal J. Economic burden of stroke across Europe: A population-based cost analysis. Eur Stroke J. 2020;5(1):17–25. doi:10.1177/2396987319883160.

11. Candio P, Violato M, Luengo-Fernandez R, Leal J. Cost-effectiveness of home-based stroke rehabilitation across Europe: A modelling study. Health Policy. 2022;126(3):183–189. doi:10.1016/j.healthpol.2022.01.007.

12. Ingram LA, Butler AA, Brodie MA, Lord SR, Gandevia SC. Quantifying upper limb motor impairment in chronic stroke: A physiological profiling approach. J Appl Physiol. 2021;131(3):949–965. doi:10.1152/japplphysiol.00078.2021.

13. Ballester BR, Maier M, San Segundo Mozo RM, Castañeda V, Duff A, Verschure PFMJ. Counteracting learned non-use in chronic stroke patients with reinforcement-induced movement therapy. J Neuroeng Rehabil. 2016;13(1):74. doi:10.1186/s12984-016-0178-x.

14. Chen J, Or CK, Chen T. Effectiveness of Using Virtual Reality-Supported Exercise Therapy for Upper Extremity Motor Rehabilitation in Patients With Stroke: Systematic Review and Meta-analysis of Randomized Controlled Trials. J Med Internet Res. 2022;24(6):e24111. doi:10.2196/24111.

15. Kwakkel G, Stinear C, Essers B, Munoz-Novoa M, Branscheidt M, Cabanas-Valdés R, Lakičević S, Lampropoulou S, Luft AR, Marque P, Moore SA, Solomon JM, Swinnen E, Turolla A, Alt Murphy M, Verheyden G. Motor rehabilitation after stroke: European Stroke Organisation (ESO) consensus-based definition and guiding framework. Eur Stroke J. 2023;8(4):880–894. doi:10.1177/23969873231191304.

16. Rahayu UB, Wibowo S, Setyopranoto I, Hibatullah Romli M. Effectiveness of physiotherapy interventions in brain plasticity, balance and functional ability in stroke survivors: A randomized controlled trial. NeuroRehabilitation. 2020;47(4):463–470. doi:10.3233/NRE-203210.

17. Huser M, Sándor PS, Frese S. Einsatz einer Virtual-Reality-basierten Therapie der oberen Extremitäten in der Telerehabilitation unter Berücksichtigung der Adhärenz und des Bedienungsverhaltens bei einer Patientin mit Multipler Sklerose: Ein Fallbericht [Use of Virtual Reality-based Upper Limb Therapy in Tele-rehabilitation Considering Adherence and Operating Behavior in a Patient with Multiple Sclerosis: A Case Report]. Physioscience. 2025;21(3):125–131. doi:10.1055/a-2514-9160.

18. Laver KE, Lange B, George S, Deutsch JE, Saposnik G, Crotty M. Virtual reality for stroke rehabilitation. Cochrane Database Syst Rev. 2017;11:CD008349. doi:10.1002/14651858.CD008349.pub4.

19. Saposnik G, Levin M. Virtual Reality in Stroke Rehabilitation: A Meta-Analysis and Implications for Clinicians. Stroke. 2011;42(5):1380–1386. doi:10.1161/STROKEAHA.110.605451.

20. Chan A, Yan J, Csurhes P, Greer J, McCombe P. Circulating brain derived neurotrophic factor (BDNF) and frequency of BDNF positive T cells in peripheral blood in human ischemic stroke: Effect on outcome. J Neuroimmunol. 2015;286:42–47. doi:10.1016/j.jneuroim.2015.06.013.

21. Hao J, Xie H, Harp K, Chen Z, Siu KC. Effects of Virtual Reality Intervention on Neural Plasticity in Stroke Rehabilitation: A Systematic Review. Arch Phys Med Rehabil. 2022;103(3):523–541. doi:10.1016/j.apmr.2021.06.024.

22. Wankhede NL, Koppula S, Ballal S, Doshi H, Kumawat R, Raju S, Arora I, Sammeta SS, Khalid M, Zafar A, Taksande BG, Upaganlawar AB, Gulati M, Umekar MJ, Kopalli SR, Kale MB. Virtual reality modulating dynamics of neuroplasticity: Innovations in neuro-motor rehabilitation. Neuroscience. 2025;566:97–111. doi:10.1016/j.neuroscience.2024.12.040.

23. Galperin I, Mirelman A, Schmitz-Hübsch T, Hsieh KL, Regev K, Karni A, Brozgol M, Cornejo Thumm P, Lynch SG, Paul F, Devos H, Sosnoff J, Hausdorff JM. Treadmill training with virtual reality to enhance gait and cognitive function among people with multiple sclerosis: a randomized controlled trial. J Neurol. 2023;270(3):1388–1401. doi:10.1007/s00415-022-11469-1.

24. Wu J, Zeng A, Chen Z, Wei Y, Huang K, Chen J, Ren Z. Effects of Virtual Reality Training on Upper Limb Function and Balance in Stroke Patients: Systematic Review and Meta-Meta-Analysis. J Med Internet Res. 2021;23(10):e31051. doi:10.2196/31051.

25. Choi YH, Paik NJ. Mobile Game-based Virtual Reality Program for Upper Extremity Stroke Rehabilitation. J Vis Exp. 2018;133:56241. doi:10.3791/56241.

26. Benadduci M, Franceschetti C, Marziali RA, Frese S, Sándor PS, Tombolesi V, Bozzi V, Rossi L. An Integrated Virtual Reality-Based Telerehabilitation Platform to Support Recovery and Maintenance of Functional Abilities Among Older Adults: Protocol for a Usability and Acceptability Study. JMIR Res Protoc. 2025;14:e68358. doi:10.2196/68358.

27. Demeco A, Zola L, Frizziero A, Martini C, Palumbo A, Foresti R, Buccino G, Costantino C. Immersive virtual reality in post-stroke rehabilitation: a systematic review. Sensors (Basel). 2023;23(3):1712. doi:10.3390/s23031712.

28. Laver K, George S, Thomas S, Deutsch JE, Crotty M. Virtual reality for stroke rehabilitation. Stroke. 2012;43(2):e20–e21. doi:10.1161/STROKEAHA.111.642439.

29. Mekbib D, Debeli D, Zhang L, Fang S, Shao Y, Yang W, Han J, Jiang H, Zhu J, Zhao Z, Cheng R, Ye X, Zhang J, Xu D. A novel fully immersive virtual reality environment for upper extremity rehabilitation in patients with stroke. Ann N Y Acad Sci. 2021;1493(1):75–89. doi:10.1111/nyas.14554.

30. Kenea CD, Abessa TG, Lamba D, Bonnechère B. Technological features of immersive virtual reality systems for upper limb stroke rehabilitation: a systematic review. Sensors (Basel). 2024;24(11):3546. doi:10.3390/s24113546.

31. Verheyden G, Nieuwboer A, Mertin J, Preger R, Kiekens C, De Weerdt W. The Trunk Impairment Scale: a new tool to measure motor impairment of the trunk after stroke. Clin Rehabil. 2004;18(3):326–334. doi:10.1191/0269215504cr733oa.

32. Fugl-Meyer AR, Jääskö L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. Scand J Rehabil Med. 1975;7(1):13–31.

33. Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, et al. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. J Am Geriatr Soc. 2005;53(4):695–699. doi:10.1111/j.1532-5415.2005.53221.x.

34. Brooke J. SUS: a "quick and dirty" usability scale. In: Jordan PW, Thomas B, Weerdmeester BA, McClelland IL, editors. Usability evaluation in industry. London: Taylor & Francis; 1996. p. 189–194.

35. Laugwitz B, Held T, Schrepp M. Construction and evaluation of a User Experience Questionnaire. In: Holzinger A, editor. HCI and usability for education and work. USAB 2008. Lecture Notes in Computer Science, vol 5298. Berlin: Springer; 2008. p. 63–76. doi:10.1007/978-3-540-89350-9_6.

36. Demers L, Weiss-Lambrou R, Ska B. Item analysis of the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST). Assist Technol. 2000;12(2):96–105. doi:10.1080/10400435.2000.10132015.

37. World Health Organization. WHOQOL-BREF. https://www.who.int/publications/i/item/WHOQOL-BREF. Accessed 17 Sep 2026.

38. Cohen S, Kamarck T, Mermelstein R. A global measure of perceived stress. J Health Soc Behav. 1983;24:386-396. doi:10.2307/2136404.

39. Lewis JR. The System Usability Scale: Past, Present, and Future. Int J Hum Comput Interact. 2018;34(7):577–590. doi:10.1080/10447318.2018.1455307.

40. Sagnier C, Loup-Escande E, Lourdeaux D, Thouvenin I, Valléry G. User acceptance of virtual reality: an extended technology acceptance model. Int J Hum Comput Interact. 2020;36(11):993–1007. doi:10.1080/10447318.2019.1708612.

41. Tuena C, Pedroli E, Trimarchi PD, Gallucci A, Chiappini M, Goulene K, Gaggioli A, Riva G, Lattanzio F, Giunco F, Stramba-Badiale M. Usability Issues of Clinical and Research Applications of Virtual Reality in Older People: A Systematic Review. Front Hum Neurosci. 2020;14:93. doi:10.3389/fnhum.2020.00093.

42. Sun WJ, Song YY, Wang C, Jiang Y, Cui WY, Liu WJ, Liu Y. Telerehabilitation for family caregivers of stroke survivors: a systematic review and meta-analysis. J Nurs Manag. 2023;2023:3450312. doi:10.1155/2023/3450312.

43. Cieślik B, Mazurek J, Wrzeciono A, et al. Examining technology-assisted rehabilitation for older adults' functional mobility: a network meta-analysis on efficacy and acceptability. NPJ Digit Med. 2023;6:159. doi:10.1038/s41746-023-00907-7.

44. Razak SS, Garcia-Torrico F, Smith CJ, Khiralla AH, Kothagundla S, Ochoa Hernandez DL, et al. Telerehabilitation and cost analysis in global neurosurgery: a systematic review and meta-analysis of 40,537 patients. Neurosurg Focus. 2025;58(3):E8. doi:10.3171/2024.12.FOCUS24830.

45. Francheschetti C, Marziali RA, Benadduci M, Tombolesi V, Casoni E, Di Donna V, Riccardi GR, Rossi L. An Integrated VR-Based Tele-Rehabilitation Platform to Support RECOVERY and Maintenance of FUNctional Abilities Among Seniors: Italian Trial Results. In: De Paolis LT, Arpaia P, Sacco M, editors. Extended Reality. XR Salento 2025. Lecture Notes in Computer Science, vol 15743. Cham: Springer; 2026. p. 153–170. doi:10.1007/978-3-031-97781-7_11.

Figures



Figure 1

Selected components of the RecoveryFun telerehabilitation prototype system: VR Headset (Pico 4) and a wearable sensor (Shimmer very pulse)

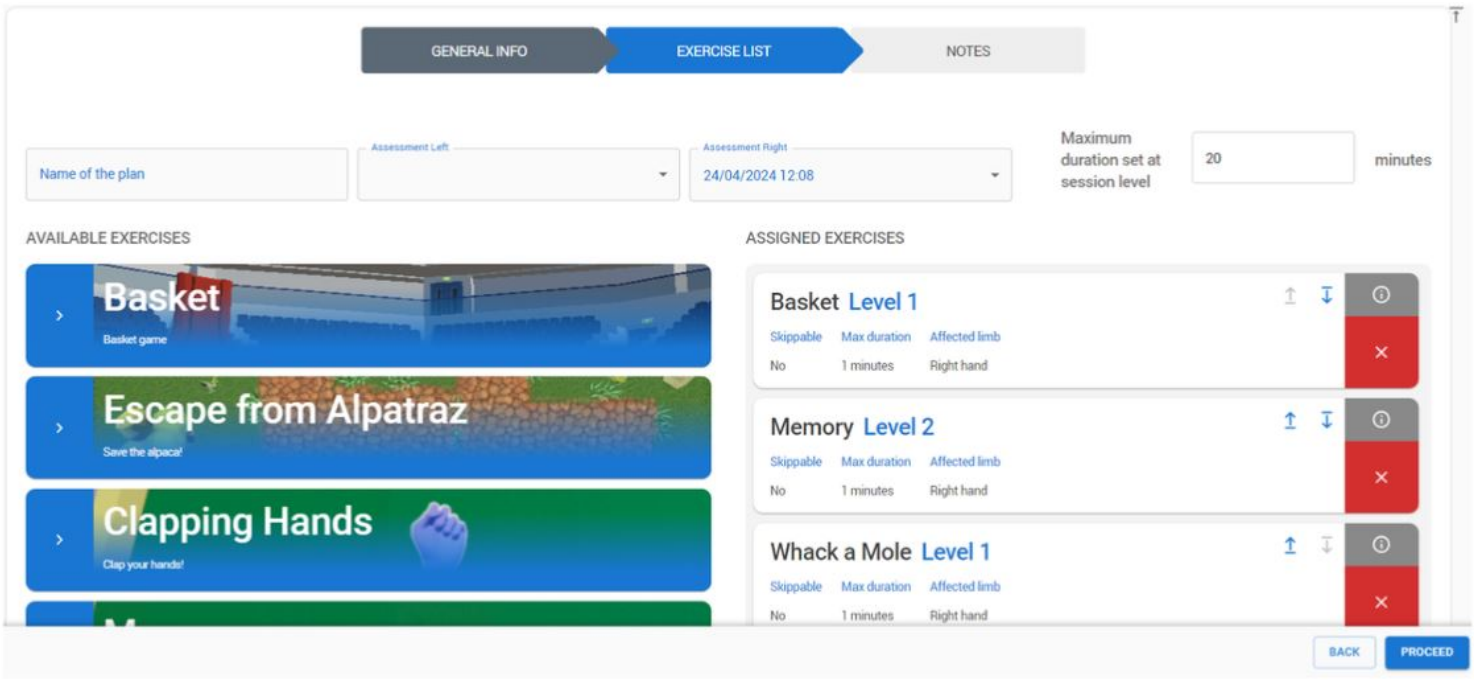


Figure 2

Exergames VR application

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementaryfile1.Patientassessmentdata.docx
- Supplementaryfile2.Caregiversassessmentdata.docx