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Human-centered solutions and synergies across robotic and digital systems for rehabilitation

Edited by
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Human-centered solutions and synergies across robotic and digital systems for rehabilitation

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Table of contents

05 Editorial: Human-centered solutions and synergies across robotic and digital systems for rehabilitation
Giacinto Barresi, Ana Lúcia Faria, Marta Matamala-Gomez, Edward Grant, Philippe S. Archambault, Giampaolo Brichetto and Thomas Platz

08 A novel immersive virtual reality environment for the motor rehabilitation of stroke patients: A feasibility study
Giulia Fregna, Nicola Schincaglia, Andrea Baroni, Sofia Straudi and Antonino Casile

20 A multiarticulate pediatric prosthetic hand for clinical and research applications
Marcus A. Battraw, Peyton R. Young, Wilsaan M. Joiner and Jonathon S. Schofield

34 Using robot-assisted stiffness perturbations to evoke aftereffects useful to post-stroke gait rehabilitation
Vaughn Chambers and Panagiotis Artemiadis

52 Feasibility, coverage, and inter-rater reliability of the assessment of therapeutic interaction by a humanoid robot providing arm rehabilitation to stroke survivors using the instrument THER-I-ACT
Thomas Platz, Ann Louise Pedersen and Stephanie Bobe

61 Analysis of the therapeutic interaction provided by a humanoid robot serving stroke survivors as a therapeutic assistant for arm rehabilitation
Thomas Platz, Ann Louise Pedersen, Philipp Deutsch, Alexandru-Nicolae Umlauft and Sebastian Bader

74 Functional improvement of patients with Parkinson syndromes using a rehabilitation training software
Marcus Barth, Robert Möbius, Peter Themann, Erdem Güresir, Cornelia Matzke, Dirk Winkler and Ronny Grunert

83 Augmented feedback modes during functional grasp training with an intelligent glove and virtual reality for persons with traumatic brain injury
Mingxiao Liu, Samuel Wilder, Sean Sanford, Michael Glassen, Sophie Dewil, Soha Saleh and Raviraj Nataraj

98 How should robots exercise with people? Robot-mediated exergames win with music, social analogues, and gameplay clarity
Naomi T. Fitter, Mayumi Mohan, Rhian C. Preston, Michelle J. Johnson and Katherine J. Kuchenbecker

116 NeuroAIreh@b: an artificial intelligence-based methodology for personalized and adaptive neurorehabilitation
Ana Lúcia Faria, Yuri Almeida, Diogo Branco, Joana Câmara, Mónica Cameirão, Luis Ferreira, André Moreira, Teresa Paulino, Pedro Rodrigues, Mónica Spinola, Manuela Vilar, Sergi Bermúdez i Badia, Mario Simões and Eduardo Fermé

134 **Design recommendations for XR-based motor rehabilitation exergames at home**
Emanuel A. Lorenz, Andreas Bråten Støen, Magnus Lie Fridheim and Ole Andreas Alsos

150 **Robotic systems for upper-limb rehabilitation in multiple sclerosis: a SWOT analysis and the synergies with virtual and augmented environments**
Giulia A. Albanese, Anna Bucchieri, Jessica Podda, Andrea Tacchino, Stefano Buccelli, Elena De Momi, Matteo Laffranchi, Kailynn Mannella, Michael W. R. Holmes, Jacopo Zenzeri, Lorenzo De Michieli, Giampaolo Brichetto and Giacinto Barresi

167 **Use of an upright power wheelchair in spinal cord injury: a case series**
Eunkyoung Hong, Michael Elliott, Stephen Kornfeld and Ann M. Spungen

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Editorial: Human-centered solutions and synergies across robotic and digital systems for rehabilitation

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Editorial on the Research Topic
Human-centered solutions and synergies across robotic and digital systems for rehabilitation

The growing need for effective, personalized, clinically compliant, and engaging rehabilitation – based on methodologies for the progressive restoration of lost functions – can leverage the step-changes offered by interaction technologies to obtain optimal results matching the initial requests of the users (patients and clinicians). Human-Centered Design approaches may disclose the full potential of such solutions, especially considering the impact of smart systems powered by robotic devices and digital settings. In particular, virtual reality (VR) and augmented reality (AR) constitute a broad sub-class of digital settings, often intertwined with serious games (including exergames devised to promote training activities) and gamification (introducing game features in non-leisure solutions) for sustaining the users' effort over time in repetitive exercises. Furthermore, they can be connected to smart mechatronic systems (especially through their artificial intelligence – AI – features) for achieving higher versatility and efficiency (making rehabilitation more sustainable for the individual and for the healthcare system as a whole, as in telerehabilitation frameworks) (Adlakha et al., 2020; Berton et al., 2020; Mohebbi, 2020; Shahmoradi et al., 2022).

Accordingly, this Research Topic aimed at collecting contributions on robotic and digital technologies for starting a wider dialectics on the groundbreaking opportunities offered by such innovations.

A first example of a digital system is proposed by Faria et al. in "*NeuroAIreh@b: an artificial intelligence-based methodology for personalized and adaptive neurorehabilitation*," remarking on the contribution of AI on optimizing neuropsychological rehabilitation through a more objective cognitive profiling and a better personalization of cognitive training. Computer-powered rehabilitation solutions are presented by Barth et al. , who promote the use of avatar-based game-like training in "*Functional improvement of patients with Parkinson syndromes using a rehabilitation training software*."

Among the investigations focusing on digital solutions, "*Design recommendations for XR-based motor rehabilitation exergames at home*" is presented by Lorenz et al. to guide the design and development of novel Extended Reality (XR, the umbrella term for all types of combinations of virtuality and reality) settings for home training. Furthermore, "*A novel immersive virtual reality environment for the motor rehabilitation of stroke patients: A feasibility study*" by Fregna et al. remarks on the potential impact of this VR technology to improve the individual adherence to clinical protocols, one of the most crucial aspects to introduce immersive settings in healthcare. Innovative solutions for enriching the user experience in VR systems devised for clinical goals are discussed by Liu et al. in "*Augmented feedback modes during functional grasp training with an intelligent glove and virtual reality for persons with traumatic brain injury*."

This Research Topic also explored studies based on mechatronic devices, such as in assistive or prosthetic robotic systems able to restore individual skills in activities of daily living (ADLs). In "*Use of an upright power wheelchair in spinal cord injury: a case series*," Hong et al. discuss the advantages of using the mentioned device in terms of objective and subjective measures of the reactions of chronic, non-ambulatory people. Furthermore, Battraw et al. present the design and characterization of "*A multiarticulate pediatric prosthetic hand for clinical and research applications*," highlighting its potential as a robust and accessible platform for translational investigations on bionic limbs.

About therapeutic interventions for motor recovery, Chambers and Artemiadis demonstrate how repeated unilateral stiffness perturbations might work for post-stroke gait re-training in their "*Using robot-assisted stiffness perturbations to evoke aftereffects useful to post-stroke gait rehabilitation*." Robots can also work as mediators of exergames, as discussed by Fitter et al. in "*How should robots exercise with people? Robot-mediated exergames win with music, social analogues, and gameplay clarity*." This last study, in particular, discloses the topic of hybrid solutions, the result of synergistic approaches mentioned in the title of this Research Topic. Indeed, the latter also aims at highlighting how synergies between digital and robotic systems can integrate and extend their advantages, offering higher versatility and engagement to their users. Such potential synergies are discussed by Albanese et al. through a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis of both robotic and virtual/augmented systems in "*Robotic systems for upper-limb rehabilitation in multiple sclerosis: a SWOT analysis and the synergies with virtual and augmented environments*," proposing to adopt their synergies for powering each other.

Interestingly, examples of such synergies can be retrieved in papers focusing on humanoid systems. Indeed, Platz et al. presented their study on "*Feasibility, coverage, and inter-rater reliability of the assessment of therapeutic interaction by a humanoid robot providing arm rehabilitation to stroke survivors using the instrument THER-I-ACT*" with a focus on a digital-humanoid robotic platform for evidence-based upper limb rehabilitation (Platz et al., 2021). Here, the authors demonstrate that therapeutic interaction by a humanoid robot as social agent can comprehensively and reliably be coded in the same way as human therapists' professional therapeutic interaction. In the paper "*Analysis of the therapeutic interaction provided by a humanoid robot serving stroke survivors as a therapeutic assistant for arm rehabilitation*" by Platz et al. it was documented that the digital therapy system E-BRAiN (Evidence-Based Robot Assistance in Neurorehabilitation; www.ebrain-science.de) that dynamically combines both knowledge about specific and diverse therapies (as implemented), therapeutic dialogue knowledge, and individual patient data showed therapeutic interaction (by the humanoid robot) that varied with type of therapy and over time (across therapeutic sessions) in as similar way as the interaction by human therapists providing the same types of therapy when administered to stroke survivors. Overall, these research papers remark on the opportunity of adopting anthropomorphic robots in combination with sophisticated digitalization of therapeutic guidance in clinical settings with a high degree of comparability to human therapy administration. This comprehensive comparability of humanoid robot-led therapy to therapy administration by human therapists opens a window of opportunity to integrate its use in healthcare settings, partially delegate tasks from human beings to humanoid robot-based systems, and hence to solve the pressing issue of an increasing demand for rehabilitation services globally and a shortage of healthcare workers globally (Feigin et al., 2023).

Summing up, this Research Topic presents several cases of investigations and solutions devised for employing the advantages of robotic and digital technologies (especially based on VR, AR, and XR paradigms) to enhance the clinical outcomes in rehabilitation, possibly extending their valuable contribution from laboratory tasks to ADLs. Possibly embracing the advantages of AI and neurotechnologies, these synergies between robotic and digital technologies pave the way for exploring novel ways to make rehabilitation systems truly centered on the human being, engaging people in repetitive activities (a task that XR systems and social robots can accomplish) and tailoring their specific clinical goals (as mechatronic devices can perform at physical level, and digital systems can in terms of cognition, behaviour, and social interaction). Intertwining the potential of both robotic and digital systems (individually and synergistically discussed in the examples provided by this Research Topic) can lead to versatile and impactful strategies in diverse types of rehabilitation: this is a perspective that should be included in the mindset of anyone working on the co-design of such technologies.

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GB: Writing–original draft, Writing–review and editing. AF: Writing–original draft, Writing–review and editing. MM-G: Writing–original draft, Writing–review and editing. EG: Writing–original draft, Writing–review and editing. PA: Writing–original draft, Writing–review and editing. GB: Writing–original draft, Writing–review and editing. TP: Writing–original draft, Writing–review and editing.

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A novel immersive virtual reality environment for the motor rehabilitation of stroke patients: A feasibility study

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We designed and implemented an immersive virtual reality (VR) environment for upper limb rehabilitation, which possesses several notable features. First, by exploiting modern computer graphics its can present a variety of scenarios that make the rehabilitation routines challenging yet enjoyable for patients, thus enhancing their adherence to the therapy. Second, immersion in a virtual 3D space allows the patients to execute tasks that are closely related to everyday gestures, thus enhancing the transfer of the acquired motor skills to real-life routines. Third, in addition to the VR environment, we also developed a client app running on a PC that allows to monitor in real-time and remotely the patients' routines thus paving the way for telerehabilitation scenarios. Here, we report the results of a feasibility study in a cohort of 16 stroke patients. All our patients showed a high degree of comfort in our immersive VR system and they reported very high scores of ownership and agency in embodiment and satisfaction questionnaires. Furthermore, and notably, we found that behavioral performances in our VR tasks correlated with the patients' clinical scores (Fugl-Meyer scale) and they could thus be used to assess improvements during the rehabilitation program. While further studies are needed, our results clearly support the feasibility and effectiveness of VR-based motor rehabilitation processes.

KEYWORDS

immersive virtual reality, stroke, motor rehabilitation, head-mount display, fugl-meyer

1 Significance statement

Approximately 80% of stroke patients suffer from a hemiparesis of the contralateral upper limb. Motor rehabilitation has been proven to be of key importance to regain, partially or totally, the impaired motor skills. Rehabilitation techniques are based on the repetitive and intense execution of simple motor behaviors. As such they can become taxing and cumbersome for the patients. This often produces non-adherence issues with an obvious negative impact on motor recovery.

Here we describe a novel immersive virtual reality environment for upper limb motor rehabilitation and we report the results that we obtained in a cohort of 16 stroke patients. Our system was designed to turn rehabilitation routines into engaging games and to allow the remote monitoring of the patients' exercises thus allowing telerehabilitation.

All our patients showed a high degree of comfort in our immersive VR system and they reported very high scores of ownership and agency in embodiment and satisfaction questionnaires. Furthermore, and notably, we found that behavioral performances in our VR tasks correlated with the patients' clinical scores (Fugl-Meyer scale) and they could thus be used to assess improvements during the rehabilitation program.

2 Introduction

Stroke is the second most common cause of death worldwide (Donnan et al., 2008; Feigin et al., 2009) and one of the main causes of acquired adult disability (WHO, 2003; Bonita et al., 2004; Warlow et al., 2008). In most patients, the acute illness produces long-term consequences for them and their families (Langhorne et al., 2011). In particular, brain damage produced by the stroke results in sensory, motor, and cognitive impairments that reduce the patient's quality of life and social participation (Miller et al., 2010). At the motor level, stroke causes deficits in one of the upper limbs in more than 80% of patients acutely and for more than 40% of them, chronically (Cramer et al., 1997). The sensorimotor recovery of the affected upper limb is a key goal of post-stroke rehabilitation, especially in consideration of its crucial impact on the patient's independence and quality of life (Pollock et al., 2014). The period immediately following a stroke is critical for regaining, at least partially, motor skills and, if specific rehabilitation programs do not take place there, patients frequently incur in long-term disabilities and reduced quality of life (Patel et al., 2006).

Neurorehabilitation aims at stimulating neuroplasticity after brain injury with the final goal of maximizing motor recovery (Sampaio-Baptista et al., 2018), and it is essential to regain, partially or totally, the impaired motor functions. It has been found that, to achieve best results, motor rehabilitation must be based on repetitive and intensive tasks (Sampaio-Baptista et al., 2018). Specifically, the execution of repetitive task training, executed in sessions repeated several times per week over several weeks, has been proven to be instrumental to increase upper limb functions in stroke patients (Veerbeek et al., 2014). Furthermore, good rehabilitation outcomes seem to be strongly and positively associated with the patient's motivation and engagement (Langhorne et al., 2011). However, due to its very repetitive nature, neurorehabilitation can quickly become cumbersome for the patients and thus produce severe adherence issues, which negatively affect the rehabilitation outcome (Paolucci et al., 2012). It is thus of outmost importance to develop enjoyable yet clinically effective training procedures.

Gamification procedures have been proposed to make the tasks more entertaining for the patients. However, such "games" are often based on simple tasks executed on a computer screen and thus partially disconnected from everyday gestures and movements. On the contrary, task-specific and context-specific trainings have been proven to be key features for the transferring of the acquired motor skills to real life (Maier et al., 2019a).

All the above issues have been recently further exacerbated by the COVID 19 pandemic that, on the one hand, resulted in a large number of Covid patients needing motor rehabilitation procedures and on the other hand created the need to move out rehabilitation procedures from the hospital to focus the limited clinical resources on the treatment of severe cases.

To address these problems, we leveraged the power of modern computer graphics to design and implement an immersive virtual reality (henceforth VR) environment for upper limb rehabilitation (Figure 1). Immersive virtual reality aims at presenting an artificial environment that replaces the user's real-world surroundings so as to elicit a convincing perception of "being real". To this end, the virtual environment has to produce strong illusions of presence (i.e., the feeling of "being there" in the virtual scenario), plausibility (i.e., the feeling that events in the virtual environment are "really happening"), and embodiment (i.e., the feeling that the body the user has in the virtual environment is "really" hers/his) (Slater, 2009, 2018; Slater and Sanchez-Vives, 2016).

Our immersive VR system solves all the major problems related to motor rehabilitation outlined above. Firstly, by leveraging the intrinsic flexibility of VR-generated environments we can present a variety of scenarios and tasks to the patients and keep them interested and focused on their rehabilitation tasks. Secondly, having the patient immersed in a full 3D environment allows us to create tasks that are closely related to everyday activities (e.g. reaching for a glass of water) thus ensuring a transfer of the acquired motor skills to real life. Thirdly, modern VR head-mounted displays are light-weight and compact and they could be easily used at home by patients. Thus, although we are presently testing our system in a clinical setting, it is already fully compatible with potential future telerehabilitation scenarios. Here, we describe the components of our system and report the results of a feasibility study in a cohort of 16 stroke patients. All our patients showed a high degree of comfort in our immersive VR system and they reported very high scores of ownership and agency in standardized embodiment questionnaires (Gonzalez-Franco and Peck, 2018). Furthermore, we found that behavioral performances in our VR tasks correlated with the patients' clinical scores and they could thus be used to assess improvements during the rehabilitation program. We discuss these findings in the

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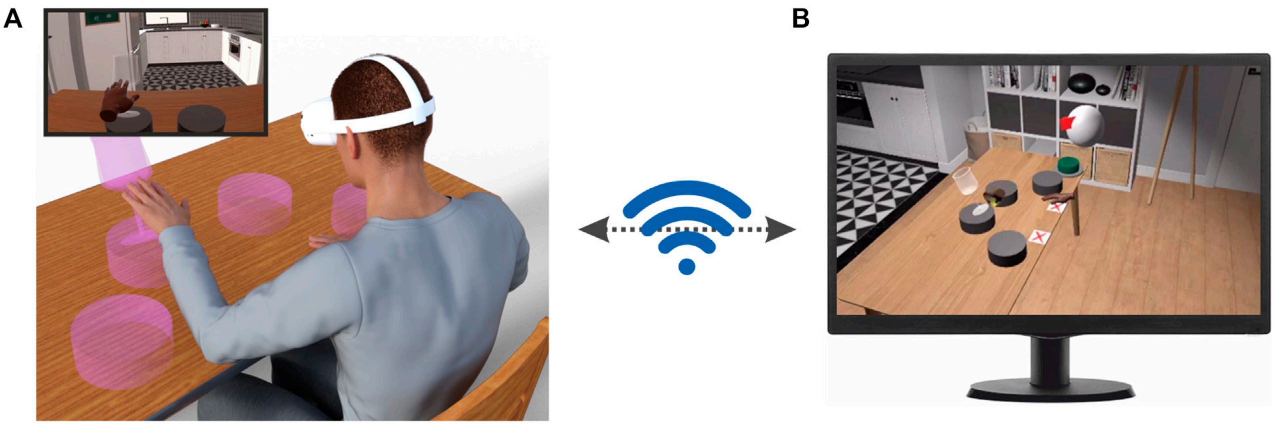

FIGURE 1
Application scenario of our immersive VR environment. **(A)** The patients are immersed in a VR environment by means of a head-mounted display (HMD, Oculus Quest 2, Facebook Reality Labs). In this environment, they can see different objects with which they can interact. The inset shows the scene as experienced by the patient on the HMD display. **(B)** The program running on the HMD wirelessly communicates with a client app running on a PC that allows to monitor remotely and in real-time the patients' behavior, set their rehabilitation routines and vocally interact with them.

context of present and future clinical scenarios with an emphasis on telerehabilitation and on the potential combination of our VR environment with robotic devices presently used in rehabilitation procedures.

3 Materials and methods

3.1 Subjects

16 subacute and chronic post-stroke patients (4 female, mean age 62 ± 9) enrolled from the Rehabilitation Units of the Ferrara University Hospital participated in the experiments. They had a wide range of motor impairments and a diagnosis of first, ischemic or hemorrhagic stroke. No age restrictions were applied but patients affected by severe cognitive impairments or other co-existing clinical conditions were excluded. The clinical protocol and all procedures were approved by the local ethical committee (Comitato Etico di Area Vasta Emilia Centro (CE-AVEC) protocol code 897/2020/Oss/AOUFe approved on 17 Marc^{h} 2021).

3.2 Experimental procedures

Prior to the experimental procedure, written, informed consent was obtained from all patients. A clinical evaluation of the upper limb impairment and functioning was performed for all the included patients. All the assessments were conducted by the same trained physical therapist. The upper limb motor recovery was assessed by means of the Fugl-Meyer Assessment - Upper Extremity (FMA-UE) (Fugl-Meyer et al., 1975).

We also collected demographic and clinical information to characterize our cohort of patients with respect to age, sex, stroke type, hemiparesis side, days elapsed from the event and hospitalization type (i.e. inpatient or outpatient).

The results of clinical assessments and patients' demographics are reported in Supplementary Table S1 in the Supplementary Information.

3.3 Embodiment questionnaire

To evaluate the degree of embodiment of the virtual hands during the experiment we used a subset of a standardized questionnaire proposed by Gonzalez-Franco and Peck, (2018). The questionnaire was administered in Italian at the end of the session and it consisted of 6 questions (see Sec 1 in the Supplementary Material). The patients could respond to each question by checking one out of 7 possible choices corresponding to a 7 point Likert scale ranging from -3 to 3, with -3 indicating strong disagreement and 3 indicating strong agreement with the statement.

Following Gonzalez-Franco and Peck, (2018), we computed the Ownership and Agency indices by combining the questionnaire's scores in the following manner:

1. Ownership (Q1—Q2)—Q3.
2. Agency: Q4 + Q5—Q6.

3.4 Satisfaction questionnaire

At the end of each experimental session, we also administered a satisfaction questionnaire (see Sec 2 in the Supplementary Material). The questionnaire was administered in Italian and it

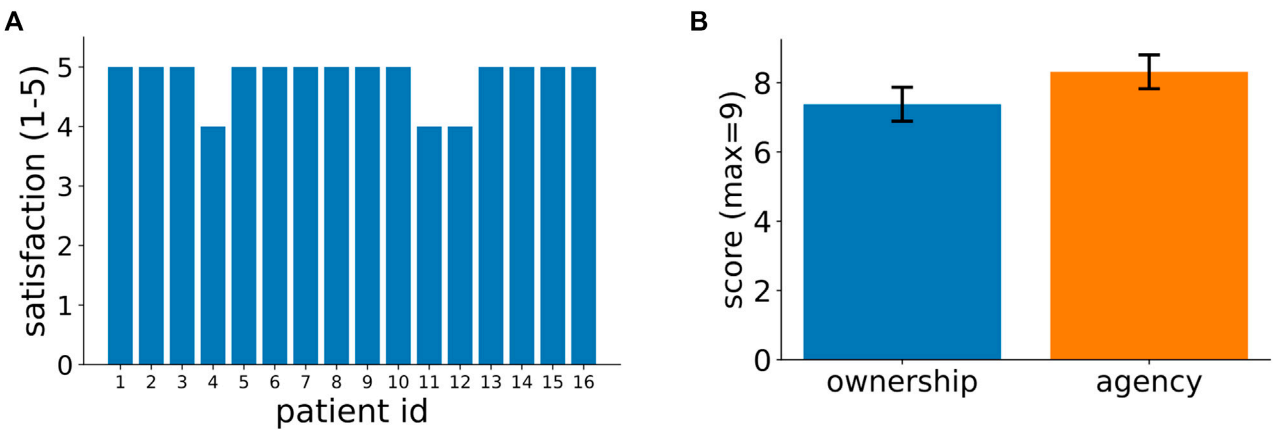

FIGURE 2
Patients' feedback on their experience in our VR-based rehabilitation system. **(A)** Patients' ratings, in a scale from 1 to 5, to the question: "Did you enjoy this type of training?" (In Italian: "Ha gradito la tipologia di allenamento?"). Supplementary Figure S3 in the supplementary information shows the responses for all other questions in the satisfaction questionnaire. **(B)** Patients' scores for ownership and agency as assessed by a standardized questionnaire (see Methods for further details). The 2 bars represent average across patients and the vertical lines signify variance (mean ownership = 7.4 ± 2.0; mean agency = 8.3 ± 2.0).

consisted of 10 items (see Supplementary Material). To six questions the patients had to respond by means of a 5-point Likert scale (1: not at all; 5: very much). Four questions had multiple-choice responses.

3.5 Immersive virtual environment and client app

Our immersive VR system was developed in C# using the Unity 3D game engine (http://www.unity3d.com). This choice was motivated by Unity's user-friendliness, easiness of learning, extensive online community and available resources (Kourtesis et al., 2020). Our system consists of two components: (1) A software package installed on the Quest 2 head-mounted display (HMD) that renders the VR environment and manages the execution of the different tasks (Figure 1A) and (2) a client app running under Windows, that wirelessly communicates with the HMD to manage the rehabilitation session (Figure 1B).

As HMD we selected the Oculus Quest 2 for four main reasons. First, it belongs to a new generation of devices that are known to substantially reduce, or even completely eliminate, potential VR induced adverse symptom and effects (VRISE) (Kourtesis et al., 2019a). Second, it has high-end technical specifications (resolution: 1832 × 1920 pixels per eye; refresh rate: 90 Hz; field of view: 90°; head tracking) that support real-time perception and enhanced immersion in virtual scenarios (Slater, 2009). Third, it has on-board capabilities that allow to visually track the patients' hand movements in real time. Fourth, it is lightweight and price-affordable.

The VR environment consists of a cozy home interior with windows showing a beachside scenarios (Scandinavian Interior Archviz purchased from the Unity Asset Store). This environment was selected based on previous studies suggesting that patients' motivation during motor rehabilitation is increased by sensory enriched environments containing access to nature and outdoors (Lipson-Smith et al., 2021). Furthermore, it has high graphical quality, a feature that is known to increase the sense of placement in the scene (Slater, 2009). During task execution, the patients sit, both in the real and virtual environments in front of a table (Figure 1A). Notably, the position of the virtual table is registered to that of the real table. During task execution, the patients' hand and finger movements, visually captured by the Oculus Quest onboard software, are used to animate two virtual hands through which they can interact with virtual objects placed in the scene (e.g. the magenta transparent glass in Figure 1A) to perform different tasks (see below). The virtual hands are displayed from a first-person perspective as it was shown that this point of view is best to elicit a strong sense of embodiment (Slater et al., 2010; Petkova et al., 2011; Maselli and Slater, 2013), potentially due to a stronger activation of the neuronal substrates of action perception (Caggiano et al., 2011; Caggiano et al., 2015; Casile et al., 2011).

During task execution, our system wirelessly communicates with a client app running on a PC that shows a faithful render of the VR environment in which the patients are immersed as well as their virtual hands from a third-person point of view (see Figure 1B for an actual screenshot of the client app). Through this app the rehabilitation therapist can in real-time and remotely monitor the patients' actions and, in case, vocally interact with them. Furthermore, by means of a pop-up menu (Supplementary Figure S1) the therapist can also manage the rehabilitation session by setting the sequence of tasks and the number of trials per task that the patient has to perform.

Notably, we designed our system such that the HMD and the client app do not need to be on the same local network, thus enabling telerehabilitation scenarios in which the patients can perform most of their routines at home while maintaining strict medical supervision. We performed no detailed technical tests to assess the bandwidth needed for the communication between the HMD and the client app. We tested, however, our VR system in a variety of scenarios ranging from hospital to home networks and even connecting to the internet using a smartphone as hotspot. In all tested conditions, the communication between HMD and the client app ran smoothly. Four tasks are presently implemented in our system, which we called Ball in hole, Cloud, Glasses and Rolling Pin respectively (see Supplementary Figure S2). *Ball in hole*: For this task, a box-like support with a pocket at its center is placed on the virtual table. At the beginning of each trial a tennis ball is placed on this support either to the right or left of the patients and they have to gently push the ball into the hole with their corresponding hand. *Cloud*: At the beginning of trial a cloud of small bubbles appears, which pop upon touching. The cloud is placed either to the right or to the left of the patients and they have to pop all of the bubbles with the corresponding hand. *Glasses*: The task starts with four pedestals presented on the table. The pedestals are distributed along a circle centered on the patient's body at equal angular displacements (The insets of Supplementary Figure S3,S4 show a simplified view from above of the pedestals). A glass then appears on one randomly selected pedestal and the patients have to push it down (Figure 1A). The patients have to use the hand closer to the pedestal on which the glass appear (two pedestals are closer to the right hand and two are closer to the left hand). *Rolling Pin*: In this task, the patients have to use both hands to move a rolling pin on the table for a pre-defined distance. These four tasks were designed to make the patients execute, in the VR environment, movements that are as close as possible to those usually performed during the rehabilitation sessions.

3.6 VR session

Upon coming to the lab, the patient was comfortably seated in a chair in front of a table. The experimenter then helped the patient to wear an HMD and immersed her/him in the VR environment depicting a home interior. In the VR environment, the patient was placed in front of a table as well. The experimenter then used calibration routines programmed in our system to set the height and distance of the table in the VR environment to match those of the real table that the patient was facing. In this manner, when touching the table in the VR environment the patient also experienced a real sensation of touch produced by the real table. This step was implemented, based on previous results showing that the experience of multi-modal (in our case, vision, touch and proprioception) matching cues enhances the feelings of embodiment, presence and immersion of subjects in a VR environment (Gallace et al., 2012; Martin et al., 2022).

The durations of VR sessions for all subjects are reported in Supplementary Table S1 of the Supplementary Materials. The average duration was 50 ± 8.6 min that is within the duration advised in previous work to avoid VRISE (Kourtesis et al., 2019b; Kourtesis et al., 2020), as also confirmed by the complete absence of any reports of adverse effects from our patients.

3.7 Correlation analysis

We related behavioral and clinical scores by means of a correlation analysis. To this end, for the subset of 9 patients for which we recorded hand trajectories, we first computed the completion times in the three single-hand tasks (ball in hole, cloud and glasses tasks) as the time difference between when the hand started moving (as obtained from the hand velocity profile) and the trial completion event. For each subject we then computed the difference, between the healthy and the impaired limb, of the median completion times. Finally, for each task, we used a one-tailed Spearman's rank-order test to correlate these differences with the Fugl-Meyer score across patients. We used a Spearman's rank-order test as we wanted to investigate the potential presence of correlations with any functional form.

For the glasses task we performed two separate correlation analyses. Indeed, in this task, glasses on pedestals 0 and 3 are closer to the left and right hand respectively compared to the glasses on pedestals 1 and 2. Therefore, completion times were different for glasses on pedestals 0 and 1 (left hand) and 2 and 3 (right hand), as can be appreciated from the distributions shown in SupplementaryFigure S3, S4. To take this into account, we computed two separate distributions: One for the difference in completion times between glasses on pedestals 0 and 3, and one for the different in completion times between glasses on pedestals 1 and 2.

4 Results

In the following, we report the results of a feasibility study of our VR system that we performed in a cohort of 16 patients. Each patient was tested once during the performance of multiple consecutive sessions, each consisting of four tasks (see Methods for a complete description of the tasks).

At the end of the experiment, all patients filled in a satisfaction and an embodiment questionnaires (Sec 1 and Sec 2 in the Supplementary Materials). Results in Figure 2A show that almost all patients gave the maximum available score of 5 to the question "Did you enjoy this type of training?". Similar close-to-maximum ratings were obtained in all other questions of the satisfaction questionnaire (see Supplementary Figure S3). The embodiment questionnaire evaluated the degree of ownership and agency produced by the virtual hands. Both scores range

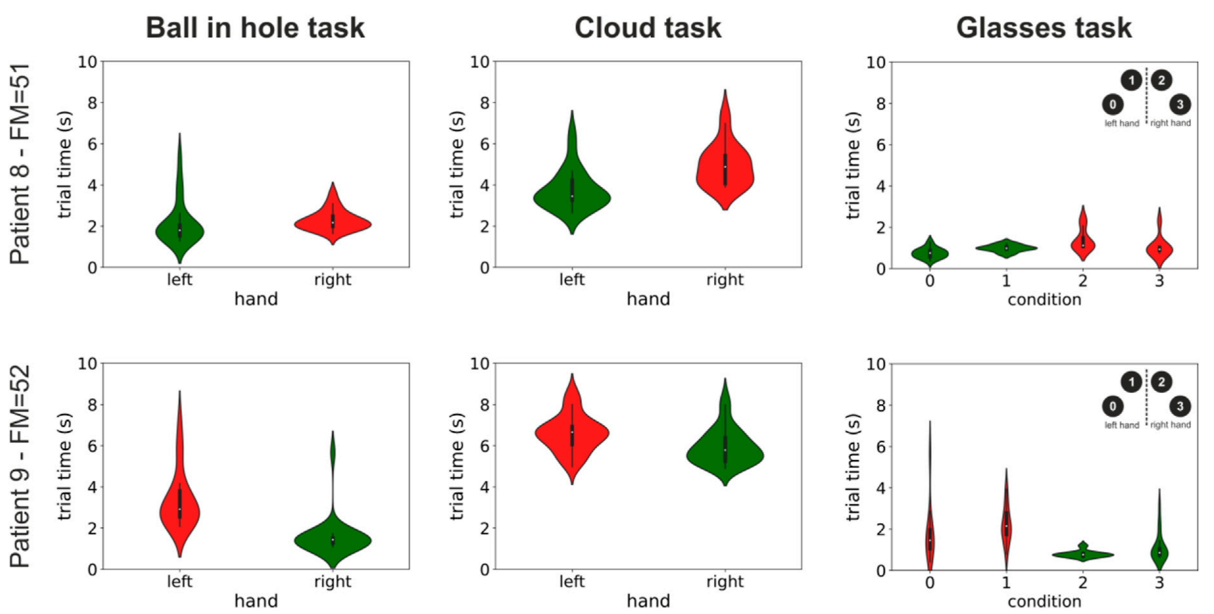

FIGURE 3
Distribution of completion times for three tasks and two patients. The violin plots show the distributions of the times taken to complete three of the tasks presently implemented in our system (three columns) for two patients. Patient 12 was a 78-year old male with a right-side impairment, and patient 13 was a 63-year old female with a left-side impairment. Distributions are color coded differently for the healthy and impaired limb (green and red respectively). The label on the vertical axis shows the patients' id and their Fugl-Meyer score. See Supplementary Figure S3 in the supplementary information for similar plots for all other patients.

from a theoretical minimum of -9 to a maximum of +9 with positive values indicating increasing levels of embodiments. The average ownership and agency scores across our patients were both very close to their theoretical maximum (mean ownership = 7.4 ± 2.0; mean agency = 8.3 ± 2.0) and significantly different from 0 (ownership: one-sample Wilcoxon test, $p<<0.001$; agency: one-sample Wilcoxon test, $p<<0.001$). In summary, the results of Figure 2 show that our immersive VR system was highly appreciated by the patients and acting by means of virtual hands produced in all of them substantial subjective impressions of ownership of the virtual body and agency.

A very promising use of our environment is that of automatically providing quantitative assessments of motor performance to the therapist to inform the rehabilitation process. This functionality is presently in an initial state and, due to continuous technical development of our system, was available only for a subset of 9 patients. It can nonetheless provide very useful information. To this end, Figure 3 shows the completion times for both the healthy and impaired limb for the three uni-manual tasks presently implemented in our system and for two of our patients: a 78-year old male (patient #12) and a 63-year old female (patient #13). As expected, in almost all conditions, completion times were significantly higher for the impaired compare to the healthy limb (patient 12: Ball in hole task: median left = 1.8s, median right = 2.17s, $p < 0.01$; Cloud task: median left = 3.45s, median right = 4.88s, $p<<0.01$; Glasses task: median condition 0 = 0.76s, median condition 1 = 0.98s, median condition 2 = 1.12s, median condition 3 = 0.93s, $p_{0,3} = 0.07$, $p_{1,2} < 0.01$. Patient 13: Ball in hole task: median left = 2.91s, median right = 1.44s, $p<<0.01$; Cloud task: mean left = 6.65 ± 0.88s, median right = 5.79s, $p<<0.01$; Glasses task: median condition 0 = 1.46s, median condition 1 = 2.15s, median condition 2 = 0.77s, median condition 3 = 0.86s, $p_{0,3} = 0.023$, $p_{1,2}<<0.001$. All *p*-values are from Mann–Whitney U tests). The distributions of task completion times for all other subjects are shown in Supplementary Figure S4.

The results in Figure 3 suggest that completions times could be potentially used to assess the progress during the rehabilitation process. Figure 4 shows the results of a correlation analysis between the differences of the median completion times between the healthy and the impaired limb and the Fugl-Meyer score across our subset of 9 patients The Fugl-Meyer score is one of the most widely used clinical assessment of upper limb motor recovery. It ranges from a minimum of 0 to a maximum of 66, with higher scores indicating less impairment. Very interestingly, we found, even in our necessarily restricted pool of subjects, a significant negative correlation between differences in completion times and clinical scores in almost all conditions (ball in hole task: correlation = -0.66, $p = 0.026$; cloud task = -0.93, $p < 0.001$; glasses task (pedestals 0 3): correlation = -0.82, $p = 0.003$; glasses task (pedestals 1 2): correlation = -0.38, $p = 0.16$; one-tailed Spearman's rank-order test). The presence of a correlation between behavioral performances in our VR tasks and clinical scores suggests that the former, that are

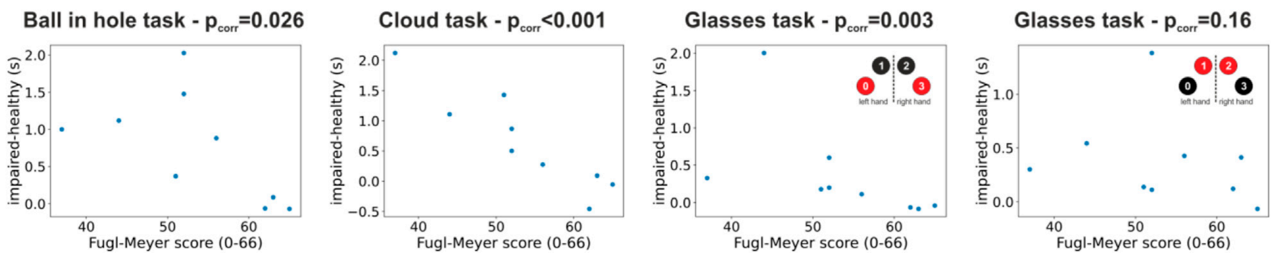

FIGURE 4
Correlation between behavioral results in our VR tasks and Fugl-Meyer clinical scores. The four scatterplots show the difference in completion times between the impaired and healthy limb for each patient and condition plotted against the Fugl-Meyer clinical assessment. Each panel shows results for one task and each dot represents data for one patients. The *p*-value of the correlation (Spearman's rank-order correlation) between completion times and Fugl-Meyer scores is shown in the panels' title.

automatically computed by our system, could be conveniently used to measure progress during the rehabilitation process. This result is very promising and it suggests that, in addition to a higher degree of patients' engagement, our system could also provide, in an automated manner, clinically meaningful indices of motor recovery to the rehabilitation therapists. Further studies in larger cohorts of patients are needed to fully validate this result.

Our system can also automatically store the patients' hand trajectories during task execution. For example, Figure 5 shows the hand trajectories recorded from a 77-year old male patient during the performance of the Ball in hole (left panel) and Glasses (right panel) tasks. As the figure shows, there are clear differences both in terms of movement span and smoothness between the trajectories of the impaired left arm and the healthy right arm. These trajectories are not presently available to therapists, unless their institution has the availability of an expensive commercial motion capture system. However, they can be easily provided by our VR system. Even their simple visual inspection, presently allowed by our system, can already give therapists relevant information concerning the trajectories of the patients' arms that can be instrumental to assess the patient's progress and inform the subsequent steps in the rehabilitation process.

5 Discussion

Here, we presented an innovative immersive virtual reality environment for upper limb rehabilitation (Figure 1) and we reported the results of a feasibility study in a group of 16 stroke patients. Almost all subjects gave the maximum rating to their experience (Figure 2A) and, in a standardized questionnaire (Gonzalez-Franco and Peck, 2018), they reported a high degree of ownership of the virtual hands and agency in the VR environment (Figure 2B). Furthermore, we found that behavioral performances in our VR tasks, that can be automatically computed, correlate with the patients' Fugl-Meyer clinical assessments (Figures 3, 4). This suggests that, in the future, they could be effectively used as an automatically computed proxy of motor recovery. Notably, our system also stores the patients' hand trajectories. Even a simple visual inspection of these trajectories (see, for example, the plots in Figure 5) can provide valuable clinical information to the expert eye and potentially inform therapeutic decisions. The very positive acceptance of our VR system by patients and the correlation that we found between behavioral performance and clinical scores do suggest that our VR system might represent a very promising direction to expand the toolbox of motor rehabilitation therapists. Furthermore, taken together, our results motivate further studies to explore and validate its clinical efficacy.

A particularly interesting and novel aspect of the present study is that we analyzed the behavioral performances of patients during performance of the VR tasks. This analysis showed that, for almost all of our tasks, the difference in task completion times between the impaired and healthy limb correlated with the Fugl-Meyer score, which is one of the most widely used clinical assessment of upper limb motor functions. This relationship suggests that differences in completion times could be used as a proxy of clinical scores, with two main advantages. First, while the computation of the Fugl-Meyer score requires a non-negligible amount of time and the involvement of specifically trained healthcare professionals, the differences in task completion times can be automatically computed by our system at the end, or even during, each training session. Second, it suggests that task completion times could be potentially used *within* a subject to monitor the efficacy of the rehabilitation process throughout its unfolding in time. We are presently testing this latter point in an ongoing longitudinal study. If these tests will have a positive outcome, then this means that our system could automatically provide ad interim clinically meaningful assessments of the progress of each patient, thus reducing the number of the more time- and resource-consuming clinical assessments. Such a scenario would represent a major step forward, with respect to existing systems, and it would greatly contribute to a more widespread adoption of VR-based motor rehabilitation systems.

It must be emphasized that the goal of our VR system is not to replace current rehabilitation therapies but rather to complement

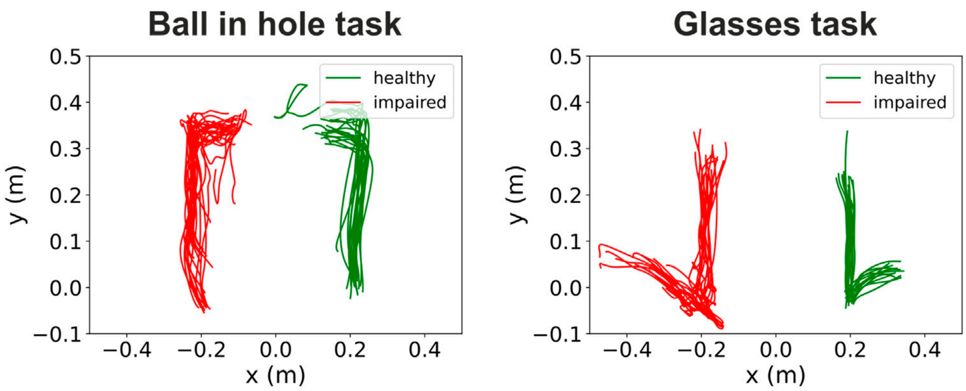

FIGURE 5
Example of hand trajectories recorded during task execution. The two panels show the hand trajectories of a 77-year old male patient during the execution of the "ball in hole" (left panel) and "glasses" (right panel) tasks. This patient exhibited a left side impairment. The trajectories of the healthy and impaired hands are shown in green and red respectively.

them and strengthen their efficacy (Fang et al., 2022) with a particular focus on two inter-related aspects: enhancing patients' adherence and provide a viable option for telerehabilitation.

Rehabilitation therapies in post-stroke patients often face adherence issues, in particular due to the need of exercises to be highly intensive and repetitive to effectively induce structural compensatory brain plasticity (Sampaio-Baptista et al., 2018). As such, they often become very tedious for the patients that end up complying only partially, or not at all, with what prescribed by the rehabilitation therapist (K. K. Miller et al., 2017). Gamification procedures have been shown to improve patients' adherence to the rehabilitation schedules (da Silva Cameirão et al., 2011; Doumas et al., 2021). In this respect, more modern solutions based on immersive VR promise to deliver a more engaging experience to patients producing therefore higher adherence to the prescribed schedules. These solutions are presently gaining increasing traction (Crosbie et al., 2012; Ögün et al., 2019; Mekbib et al., 2021), as recent technical advancements have rendered virtual reality not only extremely realistic but also extremely cost-effective and ready for the consumer market. In addition, clinical studies have proven the effectiveness of these approaches (Laver et al., 2017). Our VR system is based on the Oculus Quest 2 state-of-the-art and off-the-shelf head-mounted display and, as such, it delivers an extremely realistic VR experience at a very accessible cost. In addition, it must be emphasized that, while the Oculus Quest 2 is presently our hardware of choice, the fact that we developed our VR-based rehabilitation system in the Unity development environment using, as much as possible, standard components, ensures that it can be ported to other HMDs with minimal efforts.

Telerehabilitation is a very interesting trend allowed by recent technological advancements. That is, moving part, or even most, of the rehabilitation procedures away from the hospitals, while maintaining medical supervision. Such process has benefits both for the patients and the hospitals. Throughout the rehabilitation period, stroke patients are required to move on a regular basis (i.e. 2-3 times a week) from their houses to a hospital or other healthcare institutions to perform motor rehabilitation sessions under the supervision of trained professionals. That is very taxing for stroke patients, who are motor impaired, and it might produce additional non-adherence issues. Giving stroke patients an effective way to perform certified rehabilitation procedures at home would thus greatly contribute to increase their quality of life. This process would be also beneficial for the hospitals, as it would allow a better management of human and equipment resources, especially in view of handling potential future waves of Covid 19. With this respect, several features of our VR system were specifically implemented to support telerehabilitation scenarios and, as such, they represent a significant advancement with respect to existing immersive VR systems for rehabilitation (Crosbie et al., 2012; Ögün et al., 2019; Mekbib et al., 2021). First, the control app (Figure 1B) communicates with the HMD via the internet. Thus, the computer running the app, controlled by the rehabilitation therapist, and the HMD, wore by the patient, can be in any place with the only requirement that they both have access to the internet. Second, the client app shows an exact replica of what is experienced by the patient in the VR environment. This provides the therapist with real-time information about task performance. Third, the therapist can vocally interact with the patients and set their schedule remotely and in real-time. Fourth, our VR system estimates and stores the patients' hand trajectories during task performance. As shown in Figures 3–5, these data can potentially give relevant information to the therapist and even provide quantitative and automatic useful indications of how the rehabilitation process is proceeding. In summary, our VR system can not only greatly improve patients' adherence to prescribed therapies but has been also specifically designed to support telerehabilitation scenarios.

Virtual reality, both immersive and non-immersive, is a mature technique and it is presently experiencing an increasing trend in its adoption for clinical research, psychological interventions and cognitive studies (Blascovich et al., 2002; Lange et al., 2012; Pan et al., 2012; Slater and Sanchez-Vives, 2016; Howard, 2017; Rizzo and Koenig, 2017; Pan and Hamilton, 2018; Krohn et al., 2020; Kourtesis & MacPherson, 2021). Previous studies highlighted the promising role that it might have in the post-stroke rehabilitation of the upper limbs (for review see, for example, Doumas et al., 2021; Laver et al., 2012; Maier et al., 2019b; Mekbib et al., 2020). For example, Mekbib et al. showed that stroke patients undergoing immersive VR-based upper limb motor rehabilitation exhibited a significant increase in Fugl-Mayer score and neural activity in brain areas, particularly those implicated in mirror neurons (Rizzolatti et al., 2014; Casile, 2022), compared to a control group (Mekbib et al., 2021). In a similar fashion, Ögün et al. found a significantly higher increase in several clinical scores in patients undergoing a 6-week immersive VR-based rehabilitation program, compared to a control group (Ögün et al., 2019). Improvements in clinical scores and daily living activities were reported also in studies using non-immersive VR. In a single-group study, Perez-Marcos et al. found significant improvements in clinical scores in chronic patients (i.e. > 6month from stroke) that used a non-immersive embodied VR rehabilitation system for 10 bi-weekly session (Perez-Marcos et al., 2017) and similar outcomes, were also reported by Cameirão et al. in a randomized controlled study (da Silva Cameirão et al., 2011). Results from the present study further support, in agreement with extant literature, the use of VR as a very promising tool in motor rehabilitation. In addition, they also suggest that VR systems, in addition to a clinical outcome, might also provide automatic proxies of clinical scores that (i.e., our results in Figure 4) that can be used by the therapist to take informed decisions during the rehabilitation process.

One potential issue of our VR-based telerehabilitation system is that of privacy. That is, how can one enforce the privacy of the patients' data when they need to be necessarily transmitted over the internet? This is presently not a real issue for our VR system as it is primarily used for research purposes and information are therefore transmitted only over highly secure clinical networks. In future releases, however, when our system will be deployed in home or non-clinical settings, we plan to enforce privacy in three main ways. First, no personal information will be stored on the HMD and all patients will be identified only by a code. In this manner, the information sent over the internet from the HMD to the client app will be anonymized by design. Second, the match between codes and personal information will be stored on the therapist's PC and patients' information on such PCs are already protected by several privacy mechanisms (password protection, encrypted hard disks, firewalls, etc.). Third, a client app can connect to an HMD only if they share a key that is set at compilation time. In this manner, we can off-line and securely set the correspondence between a client app assigned to a given therapist and all the HMDs to which she/he has access.

An additional potential issue that must be addressed by any VR system is that of cybersickness that consists in adverse effects such as nausea and vomiting, postural instability, visual disturbances, or drowsiness caused by the immersion in a virtual space (McCauley & Sharkey, 1992). These adverse effects can have diverse etiologies (Keshavarz et al., 2014; Lawson, 2014; Stanney et al., 2020a) and can strongly limit the adoption of VR-based systems. While earlier HMD elicited cybersickness in a non-negligible percentage of users (Lawson, 2014), reports of cybersickness are not common in modern HMDs and they can be strongly further reduced, and potentially eliminated, by appropriate design choices (Stanney et al., 2020b; Stanney et al., 2021) or subject-specific settings (Stanney et al., 2020a). In our experiments, no patient reported symptoms of cybersickness and the majority of them reported almost no mental or physical fatigue after their VR session (see Supplementary Figure S3). This is likely due to a combination of factors. First, we used the latest generation Oculus Quest 2 HMD that is lightweight, untethered and has a very accommodating design that is known to reduce cybersickness (Stanney et al., 2020b). Second, our patients underwent interactions with the virtual environment of high ecological validity (Parsons, 2015). That is, the virtual hands were controlled in real-time by their own hands; we registered the position of the real table in front of the patient and the table in the virtual space such that the patients experienced a consistent tactile feedback when touching the table in the virtual environment with their virtual hands; many virtual objects exhibited physically-plausible behaviors (e.g., they could be pushed or moved) and we associated veridical sounds to events, where appropriate (e.g., the sound of broken glass in the Glass task). In this manner, the patients experienced, as much as possible, congruent sensorimotor contingencies that are known to increase the illusion of ownership of the virtual body, immersion, presence and plausibility (Slater, 2009; Maselli and Slater, 2013; Slater and Sanchez-Vives, 2016). Finally, our patients had to remain sit throughout the session, which strongly reduced potential visual-vestibular conflicts. These conflicts are one of the causes of cybersickness and are instead more likely during large passive or active bodily movements in a virtual environment (e.g. walking around). That said, patients in the present study were immersed in our virtual environment for the relatively short time of approximately one hour. Further studies, with longer exposures, are thus needed to conclusively exclude the emergence of potential cybersickness issues during usage of our immersive VR system.

One reason for the very positive responses that we obtained from our patients could be the well-known novelty effect. That is, the fact that perceived novelty plays a significant role in the adoption of information technology devices (Wells et al., 2010). We have no evidence either against or in favor of this interpretation. That said, we also believe that this does not represent a limitation either of our study or in the adoption of VR-based rehabilitation systems more in general. Compliance issues are a well-known problem in motor rehabilitation and consistent findings in the literature indicate that the intensity with which the patients execute their rehabilitation routines positively correlates with clinical and functional outcomes (Kwakkel, 2006; Gunnes et al., 2019). Therefore, a VR based systems, as that presented here, that are enthusiastically adopted by patients and that make them perform their assigned routines, or even extra sessions or trials, is, in our opinion, a welcome addition to the therapists' toolbox, irrespective of the subjective reasons underlying its adoption.

As concerned about future progress of our VR system, the implementation of a mirror modality (that is, a modality in which a virtual hand is animated by the movements of the contralateral real hand) can extend and increase the therapeutic applications in terms of patients' subgroups and rehabilitative goals. The use of mirror therapy has shown clinical benefits in post-stroke patients in the improvement of upper limb motor function and impairment (Thieme et al., 2018), particularly for severely impaired ones (Colomer et al., 2016; Madhoun et al., 2020). This therapeutic intervention has proven to be instrumental also for pain reduction in patients affected by Complex Regional Pain Syndrome type 1 (Cacchio et al., 2009; Pervane Vural et al., 2016), a frequent and debilitating post-stroke condition that compromises rehabilitative outcomes. The use of immersive VR-based mirror therapy, which is characterized by a more intensive cognitive stimulation, may promote greater effects in these clinical conditions.

While we see many other potential future developments for our VR-based system, a particularly interesting one is its combination with robotic platforms used in motor rehabilitation. These devices are becoming more widespread in the clinical practice and they provide a range of training conditions ranging from the passive resistance to the active assistance of single and multiple body segments during movements (Hesse et al., 2003; Iosa et al., 2012; Mehrholz et al., 2018). Robotic devices are presently routinely used in the clinical practice mainly for gait rehabilitation as they assist in supporting the patient's bodily weight during training and help leg mobility (Calabrò et al., 2016). Furthermore, it has been shown that the combination of VR and gait-assisting devices enhances the activity of brain networks specifically involved in motor planning and learning (Calabrò et al., 2017). In the past, attempts have been made to combine arm exoskeletons and immersive virtual reality for the upper limb rehabilitation (Frisoli et al., 2009; Frisoli et al., 2007; Montagner et al., 2007). However, potentially due to the bulkiness and cost of exoskeletons, those attempts never translated to the clinical practice. In the past 10 years, robotic devices for upper limb rehabilitation have made consistent progress and they are presently not only used in the clinical practice, but their clinical efficacy has been suggested by several studies (Mehrholz et al., 2018). There are thus presently exciting opportunities for combining them with immersive virtual reality and study whether this combination enhances, similar to the combination of gait training devices and VR, functional brain networks involved in upper limb motor functions.

Data availability statement

The data supporting the conclusions of this article are available from the corresponding author (AC) upon reasonable request.

Ethics statement

The studies involving human participants were reviewed and approved by Comitato Etico di Area Vasta Emilia Centro (CE-AVEC). The patients/participants provided their written informed consent to participate in this study.

Author contributions

AC and SS designed and supervised the study. AC designed and supervised the implementation of the VR system. AC and SS designed the VR tasks. GF and NS collected the data. AB performed the clinical evaluations. AC, GF and NS analyzed the data. AC drafted the manuscript. All authors approved and finalized the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frobt.2022.906424/full#supplementary-material

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A multiarticulate pediatric prosthetic hand for clinical and research applications

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Although beginning to emerge, multiarticulate upper limb prostheses for children remain sparse despite the continued advancement of mechatronic technologies that have benefited adults with upper limb amputations. Upper limb prosthesis research is primarily focused on adults, even though rates of pediatric prosthetic abandonment far surpass those seen in adults. The implicit goal of a prosthesis is to provide effective functionality while promoting healthy social interaction. Yet most current pediatric devices offer a single degree of freedom open/close grasping function, a stark departure from the multiple grasp configurations provided in advanced adult devices. Although comparable child-sized devices are on the clinical horizon, understanding how to effectively translate these technologies to the pediatric population is vital. This includes exploring grasping movements that may provide the most functional benefits and techniques to control the newly available dexterity. Currently, no dexterous pediatric research platforms exist that offer open access to hardware and programming to facilitate the investigation and provision of multi-grasp function. Our objective was to deliver a child-sized multi-grasp prosthesis that may serve as a robust research platform. In anticipation of an open-source release, we performed a comprehensive set of benchtop and functional tests with common household objects to quantify the performance of our device. This work discusses and evaluates our pediatric-sized multiarticulate prosthetic hand that provides 6 degrees of actuation, weighs 177 g and was designed specifically for ease of implementation in a research or clinical-research setting. Through the benchtop and validated functional tests, the pediatric hand produced grasping forces ranging from 0.424–7.216 N and was found to be comparable to the functional capabilities of similar adult devices. As mechatronic technologies advance and multiarticulate prostheses continue to evolve, translating many of these emerging technologies may help provide children with more useful and functional prosthesis options. Effective translation will inevitably require a solid scientific foundation to inform how best to prescribe advanced prosthetic devices and control systems for children. This work begins addressing these current gaps by providing a much-needed research platform with supporting data to facilitate its use in laboratory and clinical research settings.

KEYWORDS

pediatric prostheses, research platform, upper limb, multiarticulate prosthesis, grasping

1 Introduction

It is estimated that congenital upper limb differences occur in up to 1 in 500 live births (Giele et al., 2001), and those with unilateral congenital below-elbow deficiencies typically present malformations amenable to prosthesis prescription. These children will have one typical upper limb and one that ends below the elbow, at the level of the proximal or mid-forearm (Edmonds et al., 1981; Krebs and Fishman, 1984; Davids et al., 2006). Prosthesis prescription for these children is a complex challenge, and presently 35%–45% of prescribed upper limb pediatric prostheses will be abandoned (Biddiss and Chau, 2007). Regardless of age, factors that affect prosthesis adoption are related to the device offering sufficient function while promoting healthy social interactions (Vasluian et al., 2013). The high rate of pediatric prosthesis abandonment suggests that current devices fall short of achieving these demands and specific reasons for abandonment include the lack of useful function offered by the device (Postema et al., 1999; Wagner et al., 2007; Vasluian et al., 2013), device weight (Egermann et al., 2009; Vasluian et al., 2013), discomfort (Postema et al., 1999; Wagner et al., 2007), and social aspects related to device cosmesis (Postema et al., 1999; Vasluian et al., 2013; Franzblau et al., 2015; Oliver et al., 2018).

Standard of care pediatric prostheses provide limited functionality, typically offering only a single degree-of-freedom open/close grasping function. This is a stark departure from the immense dexterity of an intact hand that moves with 27 degrees of freedom (Agur and Lee, 1999), and the 6–9 common hand grasp movements (pulp pinch, cylindrical grasp, among others) that have been shown to account for nearly 80% of grasping movements when performing activities of daily living (Zheng et al., 2011; Feix et al., 2016). In recent years, multi-articulating motorized prosthetic hands for adults have become increasingly available. These assistive devices offer adults significant functional benefits by providing a multitude of hand grasp configurations (Belter et al., 2013). Beyond their added function, an additional advantage inherent to their hand-like designs is the anthropomorphic or more life-like appearances when compared to their hook or grasper-style counterparts. Similarly, dexterous devices have begun to emerge for children, namely, the Vincent Young three (Vincent Systems, Karlsruhe, Germany) which is sized for an 8-year-old and offers up to 13 individual grasp configurations, or the Hero Arm (Open Bionics, Bristol, United Kingdom) which offers children 8 years and older six grasp configurations.

As dexterous pediatric prostheses continue to emerge there remain many unanswered questions such as which control techniques may be most effective in operating these devices, the degree to which children can use the newly available dexterity for improved functional outcomes, and how best to translate many effective innovations for adults to meet the unique demands of children (Battraw et al., 2022a). For example, it is not known which grasping motions may be most effective to support age-appropriate daily activities and childhood play. Additionally, it is unknown how conventional adult muscle-based prosthesis control (surface EMG) may be translated to this population given that many were born with their limb difference and their affected muscles have never actuated an intact limb (Battraw et al., 2022b). Although control of dexterous prostheses for adults with congenital upper limb deficiencies has been investigated (Kryger et al., 2011), it is uncertain how these findings may translate to developing children. Furthermore, limited work has been done to illustrate changes in cortical activation during prosthesis control (Da Paz and Braga, 2007; Copeland et al., 2021). Addressing these knowledge gaps requires rigorous scientific investigations and supporting research platforms; hardware such as dexterous child-sized prostheses with open access to its programming and the mechanical capabilities to interact with daily objects to perform clinical or research-based activities. While there are no robust pediatric research platforms, there are numerous experimental or non-clinical pediatric prostheses that have been reported in literature; however, data characterizing their use, functional capabilities, and effectiveness remain sparse (Ten Kate et al., 2017). Furthermore, researchers and clinicians often have limited access to these devices as they are not commercially available, and few are released open-source such that they can be fabricated and programmed by individuals outside of their development teams.

Our objective was to develop a child-sized multi-grasp prosthesis that may serve as a robust research platform to address many of the critical gaps in translating dexterous upper limb prostheses to pediatric populations. In anticipation of an open-source release, we performed a comprehensive set of benchtop and validated functional tests manipulating common objects to quantify the performance of our device. Here we present the development of a cable-driven, underactuated, adaptive grasp, multi-articulate pediatric hand termed the Bionic Engineering and Assistive Robotics Pediatric Assistive Ware (BEAR PAW). The mechanical and electrical characteristics of individual digit articulation and seven commonly used hand grasps (Feix et al., 2016) are presented, followed by the functional performance benchmarked against other multi-grasp devices using an established assessment protocol (Llop-Harillo et al., 2019).

2 Materials and methods

We performed three tasks that were designed to develop, characterize, and evaluate the performance of the BEAR PAW. Design criteria were derived to inform the development and fabrication of our pediatric device. We performed benchtop testing to evaluate the device's mechanical and electrical characteristics, and we evaluated the BEAR PAW while

TABLE 1 Pediatric research platform design criteria.

Design requirement	Specification metric	Quantitative value
Size	Anatomical proportions	8-year-old child
Mass	Low mass	<130 g
Inexpensive	Low cost	< $1000
Degrees of actuation	Digit actuation and thumb opposition	6 degrees of actuation
Active actuation	Servo control	Servo motors
Electronics	Compact design	Enclosed in hand
Extended operation	Continuous power	Grid power
Control	Ease of actuation	Bluetooth protocol
Ease of use	High usability	Graphical interface
Finger speed	Time to close	<1 s
Load	Target mass	500 g

grasping common objects to benchmark its performance against other comparable adult devices.

2.1 Pediatric prosthetic hand criteria

In developing a robust research platform, delivering a device capable of achieving multiple hand grasp configurations to a similar degree of dexterity as current research-based adult devices was the crux of the challenge. The size of the device was an important first step to consider, as this directly impacted the feasibility of device development. As emerging dexterous devices have been targeted to no younger than the 8-year-old population and off the shelf componentry is limited in size, the minimum age of eight provides us with an ideal size constraint. Furthermore, to achieve comparable dexterity, individual digit actuation was needed along with an active opposable thumb. Weight was another important consideration during device development because children do not yet have the strength of an adult (Egermann et al., 2009). Even in a research setting, it is important to carefully consider this constraint as fatigue, soreness, and/or discomfort can significantly diminish a child's engagement with experimental activities. Here, the mass of an Ottobock Electrohand 2000 for children 8–13 years old was used as a baseline for comparison (130 g) as it is among the lightest commercially available terminal devices for children. Additionally, the force output of the device was of high importance as in biological hands, it has been shown that most hand grasping configurations on average hold objects less than 500 g in weight during most activities of daily living (Feix et al., 2016) making this an ideal design target value for a pediatric prosthesis. Further, the time to fully close the hand was set to be less than 1 *s*, reflecting values found among commercially available prosthetic systems (Vujaklija et al., 2016). Finally, a budget value of less than $1000 for parts was selected to promote the accessibility of our system to other research laboratories. A detailed summary of the design criteria is outlined in Table 1.

2.2 Mechanical and electrical performance

2.2.1 Experimental setup

We characterized the mechanical and electrical performance of the BEAR PAW while performing a set of the most frequently used generalized hand grasps along with individual digit actuations. Feix et al. (2016) suggests that the vast majority of human object manipulations are accomplished using 33 different grasp types which can be simplified to 17 generalized hand grasp configurations. This simplification can be made when considering that objects of different shapes and sizes may actually require the hand to move in similar ways, just to differing degrees of hand closure (Feix et al., 2016). This is a relevant consideration as the BEAR PAW is programmed to conform to objects regardless of their size. Of the 17 generalized hand grasps some are used far more frequently than others, and a subset of seven accounts for 80% of total activity (Table 2). Furthermore, these seven grasps also accounted for over 80% of the time duration in which a hand is used to grasp objects in daily living. Table 2 shows the top seven generalized hand grasps that were used to characterize the BEAR PAW's performance.

A set of six custom manipulanda were designed and fabricated to measure the force characteristics of the BEAR PAW while performing the seven grasp configurations and individual digit actuations. These consisted of a series of 3D printed enclosures that housed one to two calibrated 8 mm diameter SingleTact capacitive force sensor(s) with a range of 10 N (SingleTact CS8-10, PPS United Kingdom Limited, Glasgow, United Kingdom) (Table 3).

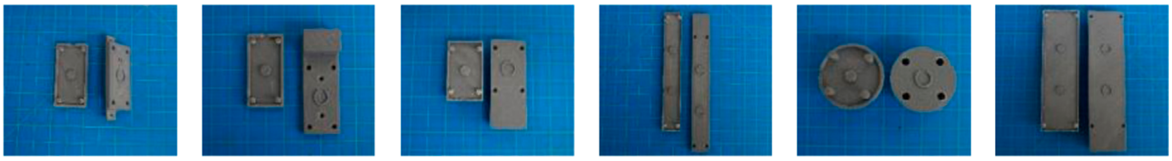
A testing platform was assembled with 15 × 15 mm MakerBeam and included a custom 3D printed mount for the

TABLE 2 Top seven generalized hand grasp configurations, percent frequency (Freq), and duration (Dur).

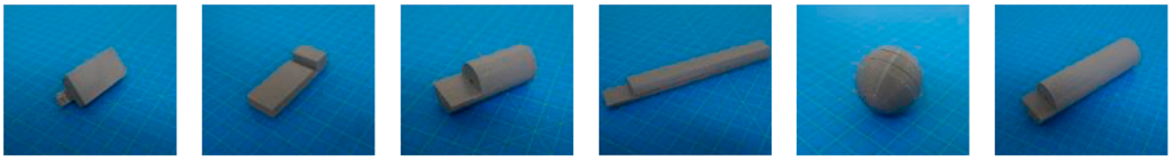
1. Cylindrical Grip	2. Tripod Pinch	3. Prismatic 4 Finger	4. Lateral Pinch	5. Lateral Tripod	6. Hook Grip	7. Pulp Pinch
Freq: 21.6%	Freq: 14.8%	Freq: 11.3%	Freq: 10.5%	Freq: 10.4%	Freq: 6.8%	Freq: 4.8%
Dur: 30.5%	Dur: 10.4%	Dur: 26.9%	Dur: 6.9%	Dur: 5.1%	Dur: 5.1%	Dur: 2.7%

TABLE 3 The different manipulanda used to characterize the force output of the BEAR PAW for individual finger articulation and common generalized hand grasp configurations. The hand grasp (HG) used and the number of sensors (NS) for each manipulandum are noted and each square on the blue background is 1 cm by 1 cm.

Top view



Isometric



Description	HG: Finger Articulation	HG: Pulp Pinch, Lateral Pinch	HG: Lateral Tripod	HG: Prismatic 4 Finger	HG: Tripod Pinch	HG: Hook Grip, Cylindrical Grip
	NS: 1	NS: 1	NS: 1	NS: 2	NS: 1	NS: 2

BEAR PAW. The platform was designed to fixate the BEAR PAW which allowed for repeated consistent testing of the various hand motions during data collection. Additionally, the platform accommodated the set of manipulanda to capture the mechanical force output. These were either mounted to the platform or on an external gooseneck for strategic object placement (Figure 1).

Beyond the mechanical force measurements obtained using the manipulanda, the electrical characteristics of the BEAR PAW were recorded during testing. This included capturing the current obtained with an ACS723 current sensor which recorded the current load of the BEAR PAW's servo motors during the experimental procedure. Further, the voltage across the servo motors during actuation was recorded. Lastly, to synchronize the data during post-hoc analysis a timing voltage was used. An Arduino script was written to actuate the BEAR PAW and the voltage values produced from the force, servo current, servo voltage, and time voltage were passed into a National Instruments USB-6210 data acquisition system sampling at 4000 Hz. This data was stored for further analysis in a table format using a MATLAB (The MathWorks, Inc., Natick, MA) script.

2.2.2 Experimental procedures

The BEAR PAW was tested to determine the mechanical and electrical performance when completing individual digit and grasp actuations. In both configurations, the BEAR PAW was mounted to the testing platform to assess the grasping movements shown in Figure 2. To test individual digit flexions, the manipulandum was placed at a fixed distance and was then aligned with the digit so that it would press down on its center. For each hand grasp configuration, the appropriate manipulandum was attached to the gooseneck (Figure 1) and was strategically placed in front of the BEAR PAW (Figure 2).

Testing was performed in accordance with ANSI/ISA testing protocols (ANSI/ISA Process Instrumentation Terminology, 1979). The test procedure consisted of performing single-digit actuations and the hand grasp configurations 10 times each. Here

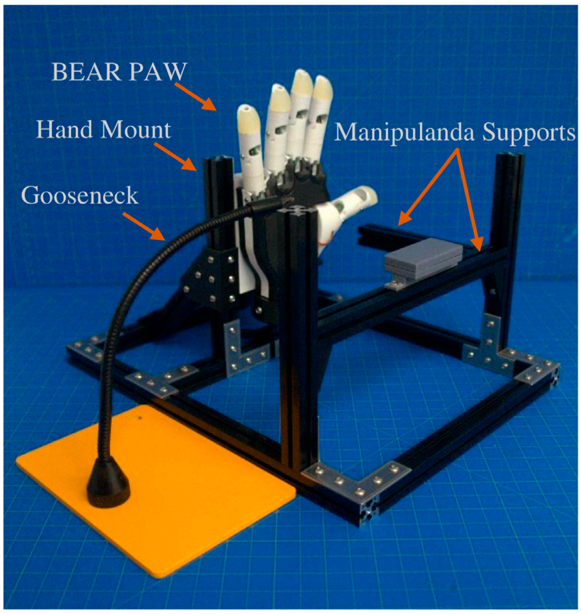


FIGURE 1
Depicts the testing platform for the BEAR PAW. It illustrates the hand mount used to hold the BEAR PAW stable during testing, the gooseneck which strategically held manipulanda, and the MakerBeam platform which supported the manipulandum used for individual digit articulation.

one cycle consisted of the BEAR PAW actuating for a total of 5 s to grasp/load the manipulandum and then unload it. The current from the servo motors, voltage across the servo motors, force applied to the manipulandum, and a reference voltage used for data synchronization, were measured and stored for each testing cycle. Together, these data allowed for post-hoc calculations relating force, current, and power each time the BEAR PAW performed a grasping movement (see below).

2.2.3 Data analysis

A separate MATLAB script was written to read the stored data for analysis. First, the voltage output from the force sensor(s) in the manipulanda was converted to force using the line of best fit for each of the calibrated sensors (User Manual: SingleTact Miniature Force Sensors. Rev 2.3, 2017). Further, in the case of two force sensors, a point load was assumed at each sensor, and data were summed together after conversion to include the total force value. The voltage from the current sensor output was converted to amperes using the provided IC sensitivity of 400 mV/A (High Accuracy, Galvanically Isolated Current Sensor IC With Small Footprint SOIC8 Package. Rev 4, 2018). Finally, Watt's law was used to calculate power draw from the measured voltage across the servo motors and the corresponding current.

To align data across the 10 trials a reference timing voltage was used, during the 5 s of actuation, that was set to low until the BEAR PAW began to actuate at which point it was set to high. Once this occurred, 1 s of the data directly after the high was omitted followed by 2.5 s of recorded data to ensure that the BEAR PAW was fully actuated on the manipulanda. For individual digit actuations and generalized hand grasp configurations these 2.5 s were averaged for a total of 10 values, one per each actuation cycle. Here, the mean and standard deviation of these measures were obtained. Measures

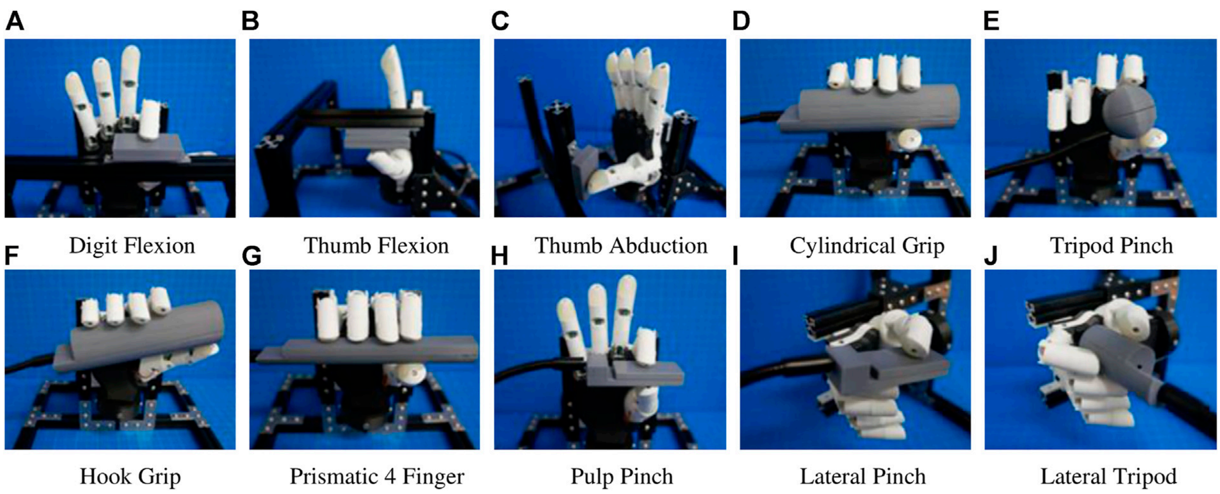


FIGURE 2
Depicts the BEAR PAW during grasp actuation on the various manipulanda. **(A)** Represents individual digit articulation for digits 2–5 and **(B–C)** represents both thumb palmar abduction and flexion. **(D–J)** Shows each manipulandum used for the seven common generalized hand grasp configurations.

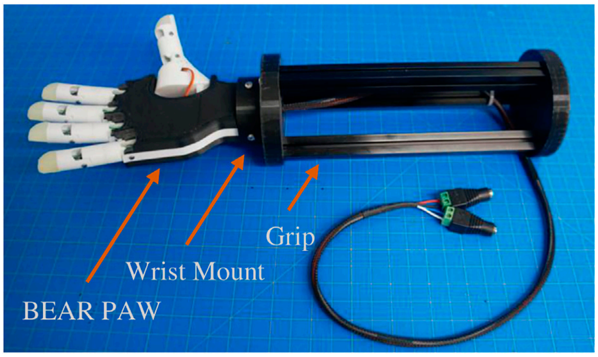


FIGURE 3
Depicts the testing rig used to perform the Anthropomorphic Hand Assessment Protocol, highlighting the BEAR PAW, wrist adapter mount, and forearm frame grip.

obtained during the flexion of digits 2–5 were averaged together as these fingers are identical in size and mechanical design. Values for thumb flexion and opposition were captured separately. Additionally, all generalized hand grasp configuration measures were averaged on an individual grasp basis.

2.3 Hand assessment protocol

2.3.1 Experimental setup

To assess the BEAR PAW's functional capabilities, we used the validated Anthropomorphic Hand Assessment Protocol (AHAP) (Llop-Harillo et al., 2019). The protocol consists of eight different grasp types of which there are three different objects associated with each. The eight grasps are Hook Grip, Spherical Grip, Tripod Pinch, Extension Grip, Cylindrical Grip, Diagonal Volar Grip, Lateral Pinch, and Pulp Pinch. Furthermore, there are two postures—Index Pointing and Platform—for a total of 26 objects that must be grasped and/or maintained. A further explanation of the objects used during the AHAP test can be found in (Llop-Harillo et al., 2019) and a subset of these objects are depicted in the results section.

We preprogrammed grasp configurations into the BEAR PAW in accordance with the definitions used in (Llop-Harillo et al., 2019). These definitions explained the proper posture for each grasp and indicated the correct contact between an object and various locations on a robotic hand. With these definitions, the BEAR PAW's hand grasp configurations were created in software by adjusting individual digit positions which allowed for it to appropriately conform to the test objects. This was achieved using a custom developed graphical user interface (GUI) that allowed the investigators to fine-tune the digit movements for each grasp configuration using virtual buttons and knobs. The final settings were stored, and the GUI offered the ability to then simply press a virtual button to actuate the final grasping configurations. To perform the AHAP protocol a testing rig was developed which consisted of the BEAR PAW mounted to a forearm frame through a wrist mount (Figure 3) which could then be held by the investigator to perform necessary object manipulations.

2.3.2 Experimental procedures

The AHAP test required that 26 test objects be manipulated 3 times which was then repeated by three test investigators (Llop-Harillo et al., 2019). Replicating the test with 3 separate investigators is the standard AHAP procedure and ensures that collected data accounts for the minor potential variability in the way objects may be manipulated. Here, investigators included laboratory personnel who acted as the lead investigator and test investigators. Prior to conducting the protocol the test investigators were instructed by the lead investigator as to the correct hand grasp for the object and were allowed to familiarize themselves for approximately 1 min (Llop-Harillo et al., 2019). Each trial of the AHAP protocol began with the lead investigator holding 1 of the 26 objects in front of a test investigator in a predefined orientation. The test investigator utilized the GUI to actuate the BEAR PAW to achieve a desired grasp configuration and grasp the object. Afterwards, the lead investigator would release the object such that it was held exclusively by the BEAR PAW. For each grasp type (excluding postures), the BEAR PAW started in the palm faced up direction in which it attempted to hold the corresponding object for 3 s (known as the grasping phase) and then was rotated 180 ° with the palm faced down again attempting to hold the object for 3 s (known as the maintaining phase). The index posture consisted of starting a timer for the grasping phase and stopping it after 3 s for the maintaining phase. Additionally, the platform posture only involved the grasping phase which entailed holding a plate for 3 s. The grasping and maintaining phases for each grasp type and posture are further described in (Llop-Harillo et al., 2019).

2.3.3 Data analysis

During the grasping and maintaining phases for each object, the lead investigator scored the BEAR PAW's performance (Llop-Harillo et al., 2019). Accordingly, a score of one was received if the object was held with the specified grasp for the allotted time. A score of 0.5 was received if the BEAR PAW held the object for the designated time but was done with a different grasp and 0 was received if it could not hold the object. Then, while the BEAR PAW performed the maintaining portion, if there was no movement of the object with respect to the hand over

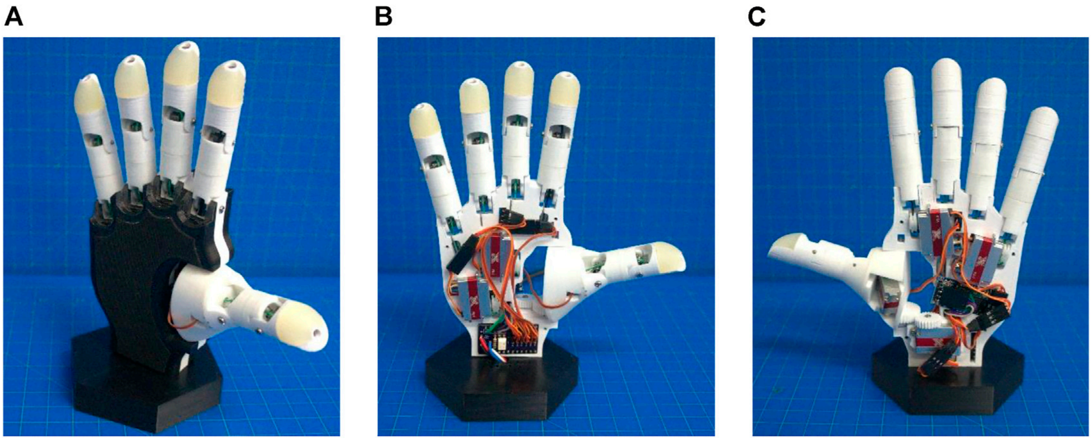


FIGURE 4
The BEAR PAW: A pediatric multiarticulate prosthetic hand with six degrees of actuation and programmable hand grasp configurations. Shown in an isometric **(A)**, front **(B)**, and back **(C)** view.

the time constraint a score of one was awarded. If the object moved but did not drop then a score of 0.5 was received and a score of 0 was received if it was not able to maintain the object. The BEAR PAW's raw AHAP scores are provided in the supplementary material.

These scores were then used to compare the BEAR PAW's grasping and maintaining abilities to previously published values from four research-focused adult prosthetic hands performing the same experimental procedure (Llop-Harillo et al., 2020). These four adult hands (Dextrus, IMMA, InMoov, and Limbitless) were all underactuated systems with a range from 14 to 17 degrees of freedom and 1–6 degrees of actuation (Llop-Harillo et al., 2020). Here, scores obtained from the BEAR PAW and the four adult prosthetic hands were separated based on which phase (grasping or maintaining) the prosthetic hand was in. The scores for each prosthetic hand were further separated into 10 categories for grasping and nine categories for maintaining in accordance with the grasp type/posture. These scores were aggregated across the three test investigators such that individual grasping and maintaining comparisons could be made between the BEAR PAW and the four adult prosthetic hands.

To accommodate the ordinal (non-parametric) AHAP scoring data, statistical analyses were conducted using a Mann-Whitney U test to perform pairwise comparisons between the BEAR PAW and each of the four adult prosthetic hands (for the 10 grasps and nine postures, 40 and 36 comparisons, respectively). For each comparison, the null hypothesis H_o was that the central tendency or median score of both the BEAR PAW and the adult hand that was being compared are not significantly different for a given grasp. A confidence interval of 95% was selected and $p < 0.05$ was taken to indicate statistical differences.

3 Results

3.1 Pediatric prosthetic hand

The BEAR PAW is a multi-articulating pediatric prosthetic hand developed in the computer automated design software SolidWorks 2020 and fabricated with a SigmaX R19 3D Printer using PLA material. The BEAR PAW utilizes a 3.3 V Arduino Pro Mini with an ATmega328 microcontroller, HC-05 wireless Bluetooth module, and a custom breakout board to interface with the six KST-X08 series servo motors. Further, it internally houses its electronics, has six independently programmable degrees of actuation, is an under-actuated system with 11 degrees of freedom, and is therefore capable of a multitude of common grasping movements. In summary, the BEAR PAW is a dexterous pediatric prosthetic hand that was designed using off-the-shelf components, highly accessible design and fabrication techniques, and open access programming which includes a graphical user interface for intuitive control. A detailed depiction of the BEAR PAW is presented in Figure 4 and a detailed list of its performance characteristics is supplied in Table 4.

The BEAR PAW's design and development was inspired by the HANDi Hand and was sized to 50th percentile 8-year-old male and female anthropometric hand data (Figure 5) (Snyder et al., 1977; Brenneis et al., 2017; Cheng et al., 2019). Similar to the HANDi Hand the BEAR PAW is accessible to researchers

TABLE 4 BEAR PAW achieved specifications. *Values obtained as explained in the Materials and Methods subsection on Mechanical and Electrical Performance and the detailed analysis are provided in the corresponding Results section. †The STL files and assembly guide can be found at https://github.com/BEAR-Labs/BEAR-PAW.

Specification	Achieved value
Size/Appearance	
Anatomical proportions	8 years old child
Electrical	
Operating voltage	5 V
Actuation power	3.388–8.718 W*
Mechanical	
Time to grasp	0.67 s
Force	0.424–7.216 N*
Number of actuators	6
Type of actuators	Servo motors
Actuation type	Underactuated
Actuation mechanism	Tendon driven
Range of motion	
Degrees of freedom	11
Digit 2–5 flexion	120 degrees
Thumb flexion	90 degrees
Thumb abduction	90 degrees
Control	
Able-bodied control	Graphical interface
Communication	Bluetooth, UART
Weight	
Mass	177 g
Ease of access	
Cost	500 USD
Componentry	Off the shelf
STL Files	Available online†
Assembly guide	Available online†

and clinicians, and provides open source 3D printable files, a bill of materials, assembly instructions, microcontroller code, and GUI which can be found *via* https://github.com/BEAR-Labs/BEAR-PAW.

3.2 Mechanical and electrical performance

The BEAR PAW uses an underactuated tendon-driven design in each digit to achieve flexion, and torsion springs incorporated into each joint to return digits to their extended position when not being actuated (Figure 6A). Here flexion is caused by a servo motor rotating a pulley to which a tendon is attached. One challenge with conventional tendon-driven actuation is managing the slack that may present in the tendon. Therefore, we developed a tensioning mechanism in which a tensioner screw translates a tendon mount to

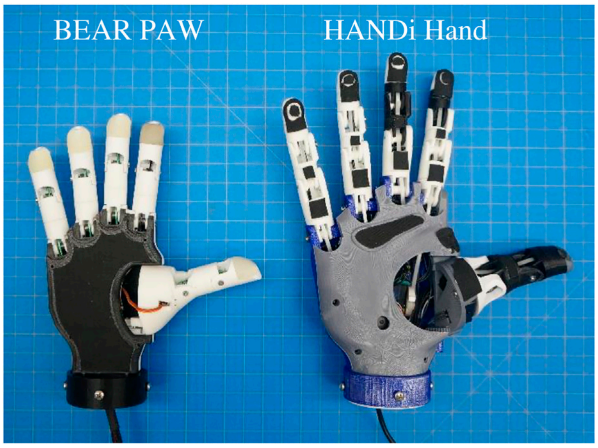


FIGURE 5
A size comparison between the BEAR PAW, a pediatric prosthetic hand, and the HANDi Hand, an adult prosthetic hand. Left shows the BEAR PAW and right shows the HANDi Hand. Each square in the background is 1 cm by 1 cm.

compensate for the slack. Moreover, the digits 1–5 are all actuated and controlled independently; while thumb abduction uses gearing for motion and is also actuated independently.

The anatomical design of digits 2–5 for the BEAR PAW included the distal, middle, and proximal phalanx where the distal and middle are coupled to accommodate the small size required of a pediatric hand. The range of motion for these digits during flexion (while not contacting objects) was approximately 60° for the proximal and middle-distal phalanx. Further, digit 1 included the distal and proximal phalanx along with the thumb metacarpal. During thumb flexion a 70° range of motion for the proximal and 20° for the distal was achieved, respectively. Finally, thumb abduction had a 90° range of motion (Figure 6B).

The measured force outputs for the BEAR PAW while performing the seven grasping configurations and individual digit articulations ranged from 0.424 N to 7.216 N. The maximum value of 7.216 N was achieved during Cylindrical Grip while the minimum value of 0.424 N was achieved during the Lateral Pinch (Table 5). The electrical performance ranged from 0.675 to 1.789 A and 3.388–8.718 W across the different grasp configurations. The minimum values of 0.675 A and 3.388 W corresponded to the individual digit flexion of digits 2–5. The maximum values of 1.789 A and 8.718 W were achieved from the Cylindrical Grip which also achieved the highest grasping forces (Table 5).

3.3 Hand assessment

When statistically comparing the BEAR PAW's grasping performance to published values of the four research-focused adult prosthetic hands, its performance scored better or

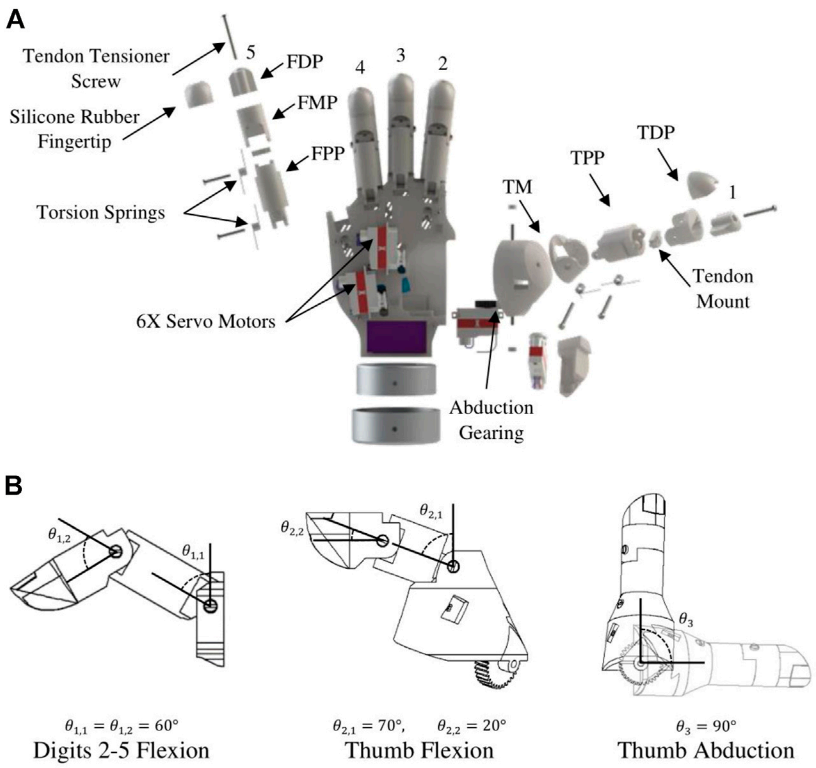


FIGURE 6
A detailed illustration of the mechanical features of the BEAR PAW. **(A)** Shows an exploded view of individual digits 1–5 highlighting key components of the mechanical design. **(B)** Provides the range of motion for each degree of actuation. Digits 1–5 are labeled with acronyms: finger distal phalanx (FDP), middle phalanx (FMP), proximal phalanx (FPP), thumb distal phalanx (TDP), proximal phalanx (TPP), and metacarpal (TM).

equivalent for 33 of the 40 comparisons made (10 grasps for four adult hands) (Figure 7). Further, 31 times out of 36 the BEAR PAW performed statistically better or equivalent during the maintaining phase for the nine grasp type/posture categories (Supplementary Material). That is, minor differences exist between the BEAR PAW and the four adult prosthetic hands when comparing grasping and maintaining capabilities.

For the grasping phase of the AHAP test, the statistical analysis showed the BEAR PAW performed significantly better a total of 9 times across the four adult prosthetic hands. Further, 24 times there were no statistically significant differences observed during the grasping phase. Finally, when comparing the BEAR PAW to each adult prosthetic hand the analysis showed statistically worse performance for seven of the grasp types/postures. A detailed analysis of the grasping comparisons from the BEAR PAW to each of the four adult prosthetic hands across the 10 grasp types/postures can be seen in Figure 7. In this figure, the number of times the hand scored a 1, 0.5, or 0 for a grasp type/posture was tallied and plotted. Further, this figure depicts a subset of the 27 objects used in the AHAP test as a reference.

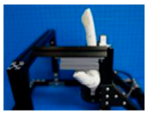
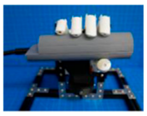
The statistical analysis for the maintaining phase of the AHAP test showed significant differences between the BEAR PAW and each of the four adult prosthetic hands. There was a significantly better performance for 16 grasp types/postures, 15 were shown to have no significant differences, while five showed statistically worse performance. The detailed statistical comparison for the maintaining phase of the test can be viewed in the Supplementary Material.

For both the grasping and maintaining phases of the AHAP test, the BEAR PAW performed significantly worse for the Hook Grip a majority of the time with only one comparison that showed no significant difference. Additionally, the BEAR PAW performed significantly better for the Pulp Pinch across all adult prosthetic hands. Finally, for the maintaining phase, the Cylindrical Grip of the BEAR PAW showed significantly better results than the other prosthetic hands. In summary, the BEAR PAW performed similarly to the four adult prosthetic hands and in some cases better, making it an effective platform to examine prosthetic control in pediatric populations.

4 Discussion

This work presents the design and characterization of a multiarticulate pediatric-sized prosthetic hand that may serve

TABLE 5 BEAR PAW's mechanical and electrical characteristics for the six degrees of actuation and the top seven generalized hand grasp configurations. *Hook Grip and Diagonal Volar Grip have the same gross hand motion, yet in the AHAP test these are considered separate motions which include a different set of objects.

Motion posture	**Motion picture**	**Mechanical and electrical characteristics**		
		Force (Newtons)	*Current (Amperes)*	*Power (Watts)*
Digits 2–5 Flexion		1.709 ± 0.076	0.675 ± 0.069	3.388 ± 0.343
Thumb Flexion		0.761 ± 0.042	0.751 ± 0.002	3.763 ± 0.010
Thumb Abduction		2.454 ± 0.069	0.729 ± 0.003	3.656 ± 0.014
Cylindrical Grip		7.216 ± 0.578	1.789 ± 0.052	8.718 ± 0.242
Tripod Pinch		2.989 ± 0.253	1.433 ± 0.035	7.030 ± 0.166
Prismatic 4 Finger		5.714 ± 0.190	1.644 ± 0.068	8.011 ± 0.316
Lateral Pinch		0.424 ± 0.011	0.841 ± 0.008	4.115 ± 0.042
Lateral Tripod		0.629 ± 0.072	0.840 ± 0.005	4.097 ± 0.024
Hook Grip/Diagonal Volar Grip*		1.415 ± 0.158	1.083 ± 0.020	5.276 ± 0.109
Pulp Pinch		2.043 ± 0.025	0.949 ± 0.004	4.649 ± 0.020

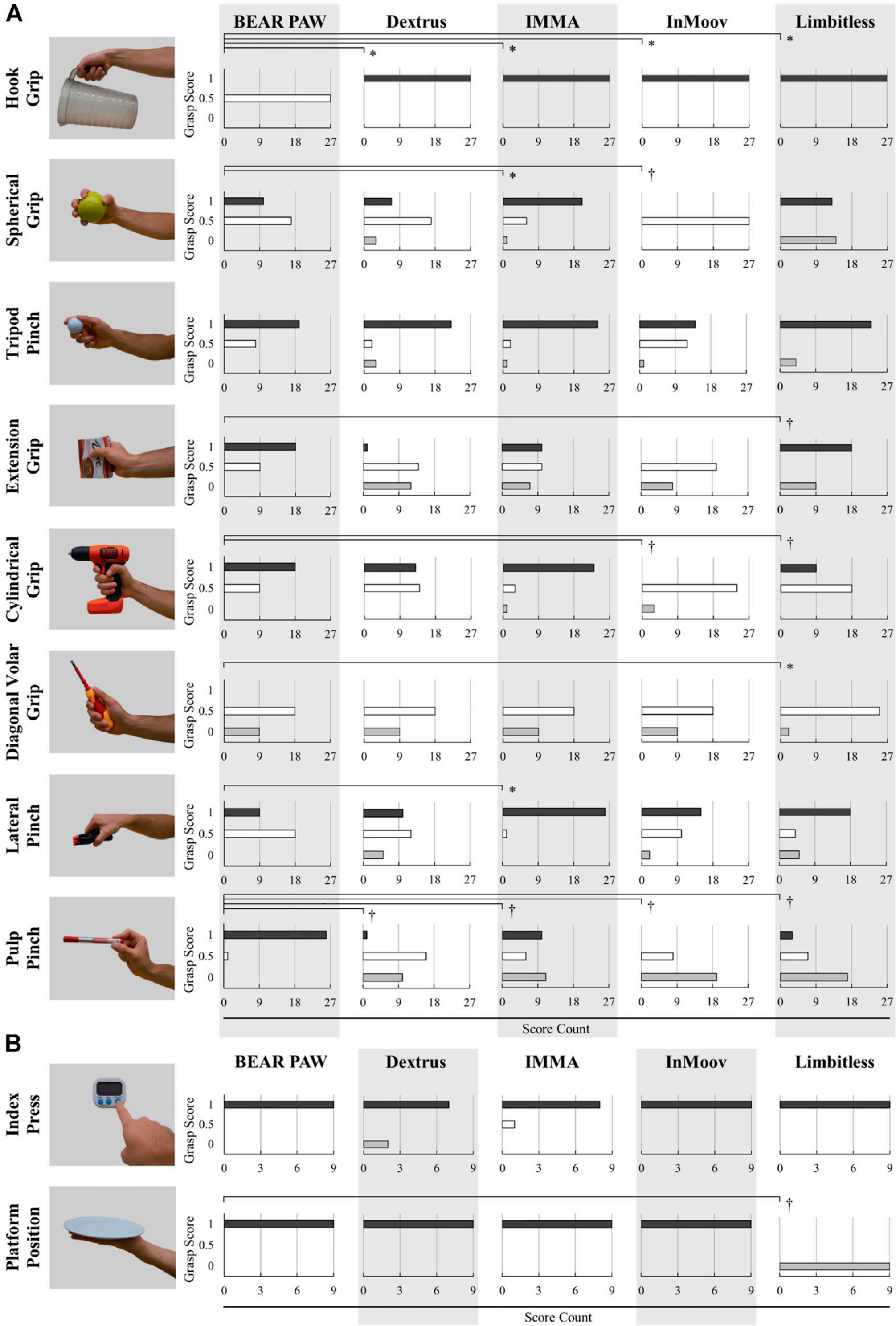


FIGURE 7
BEAR PAW grasping comparison scores for the 10 different **(A)** grasp types and **(B)** postures across the four adult hands. For each grasp type/posture, the number of times each hand scored a 1, 0.5, or 0 was plotted. *Represents when the BEAR PAW performed statistically worse. †Represents when the BEAR PAW performed statistically better.

as a robust and accessible research platform. The series of benchtop tests performed in this study provide a benchmark analysis of the device. Its performance, when compared to research-focused adult prosthetic hands, suggests that the BEAR PAW has the potential to serve as a useful tool in exploring the multitude of questions and unique challenges surrounding the effective translation of advanced mechatronic prostheses to children.

Multiple, clinically relevant design criteria were employed to inform the design and fabrication of the BEAR PAW and to ensure its utility as a research platform. These criteria included a size and weight limit, device dexterity, control methods, and accessibility. Intuitively, these criteria are interconnected and directly influence one another. A prominent example of this relationship is as dexterity increases, the number of actuators must also increase, and with that, the weight and the compact size of the device become difficult to address. This issue is vital to the BEAR PAW as it is a highly dexterous device, that is, tailored to conform to the anthropomorphic nature of an 8-year-old child to meet the need for a child-sized dexterous device. Although it is possible to develop smaller dexterous devices targeted at a younger population (less than 8 years old), commercial devices have yet to emerge, and it is unlikely a research platform with off the shelf componentry could exist as the next step to miniaturization would require hardware development. Furthermore, while the BEAR PAW exceeded the target weight limit of 130 g (weighing 177 g), the device weighs less than comparable dexterous pediatric hands such as the Hero Arm hand [280–345 g, (Hanger Clinic, 2019)], and is designed to be used in a research setting, allowing the researcher opportunities to make necessary adjustments to test procedures thereby minimizing subject fatigue.

As children's motor systems are still developing and they are often still exploring interactions within their environments, a more dexterous device is vital to allow them to interact with objects in different ways using a multitude of hand gestures (Battraw et al., 2022b). The BEAR PAW can achieve similar dexterity to that of the comparable adult prosthetic hands, providing researchers control over individual digit movements and thus, the ability to explore the effects of providing users multiple grasping configurations. Further, the BEAR PAW can accommodate multiple communication protocols and incorporates affordable off-the-shelf componentry to provide ease of use and accessibility to research groups. The 3D printable files, assembly instructions, bill of materials, and necessary code are openly available to further facilitate this access (https://github.com/BEAR-Labs/BEAR-PAW). Well-documented and tested open-source pediatric hands are scarce making experimentation with these devices difficult. Furthermore, current commercially available devices inhibit researchers' ability to manipulate device hardware/software to push the boundaries of the current state of pediatric prostheses. Here, we begin to address this gap by disseminating an open-source research platform with documented performance characteristics and benchmarking it to well-known adult research devices.

Feix et al. (2016) suggest that the majority of objects that adults commonly manipulate in daily life do not exceed 500 g, and the grasping force of the hand is largely driven by the mass of the object. The BEAR PAW achieved a maximum grasping force output of 7.216 N which exceeded the typical force required to statically grasp a 500 g object (Feix et al., 2016). This maximum force output was obtained from the Cylindrical Grip configuration, which was anticipated, as all the digits actuated around the object to perform the grasp thereby utilizing the combined outputs of all servo motors. Conversely, the minimum force output of 0.424 N was associated with the Lateral Pinch grasp and the low force was likely due to the nature of the index finger's range of motion which was limited by the servo motor to 120°. This limited range of motion caused restricted contact between the thumb and index finger. When taken together, the BEAR PAW was able to perform seven common generalized hand grasp configurations successfully, although the device could not achieve the necessary force required to manipulate 500 g objects for every hand grasp configuration. Further design refinements including incorporating high-performance servo motors may be warranted in future work.

Additionally, the electrical characteristics of current and power were tabulated to provide a baseline of electrical performance. It was found during testing that the lowest current and power draw were 0.675 A and 3.388 W, respectively. These results corresponded to the actuation of digits 2–5, which was anticipated as a single digit was being activated and with minimal frictional forces present when compared to individual thumb flexion or geared thumb opposition. Likewise, the value for the maximum current and power draw was 1.789 A and 8.718 W which were recorded from the Cylindrical Grip. Similar to the maximum force, these values were expected as all the servo motors were under load causing an increase in the current and power. Overall, these values provide the necessary information to allow for future untethered battery-operated control.

The AHAP test allowed for the BEAR PAW's grasping and maintaining ability to be evaluated when manipulating common household objects and benchmarked against the adult prosthetic hands. The objective of performing the comparisons was to validate the BEAR PAW's performances and viability as a research platform. Here it was found that the BEAR PAW performed similar to or better than comparable adult devices across the test. While it outperformed the tested adult prosthetic hands for Pulp Pinch during both the grasping and maintaining phases, this was likely attributed to the silicone fingertips that allow for increased friction when performing pinch-type manipulations. During the Cylindrical Grip maintaining phase, the BEAR PAW performed better than the other comparable adult prosthetic hands which is intuitive when viewing the mechanical force output of the Cylindrical Grip as it exhibited the highest force output of 7.216 N. However, the BEAR PAW was challenged in performing some functions. The main limitation was the size constraints required to accommodate the pediatric population. Off the shelf micro servo motors that meet these size demands are often restricted in their range of motion, thereby affecting the BEAR PAW's ability to adequately grasp and maintain certain objects, i.e., the Hook Grip could not fully wrap around smaller objects in the AHAP test. Both the small nature of the design and the limited range of motion affected the AHAP test as certain objects were too big for the BEAR PAW to reach around and too small for the range of motion.

Our data suggest that it is plausible for the BEAR PAW to be used in research and clinical settings to perform tasks and object interactions that may not be overly mechanically demanding such as box and blocks (Mathiowetz and Weber, 1985; Hebert et al., 2014), Jebsen/Taylor hand function (Jebsen et al., 1969), clothespin relocation (Kyberd et al., 2018), and the SHAP test (Light et al., 2002), among others. However, with the exception of the SHAP test (Light et al., 2002), the remaining standardized tests are not designed to challenge the patient to perform more than one grasp type/posture. Although the SHAP test (Light et al., 2002) allows for multiple grasps it uses everyday objects that may not translate effectively to the pediatric population e.g., small hand compared to object size and lack of participant engagement during testing. Therefore, the BEAR PAW can be used to explore the extent to which children can utilize multi-grasp functionality, but like the need for a robust research platform, standardized functional tests that challenge children to perform age-appropriate multi-grasp tasks are also needed. As multi-grasp pediatric devices continue to emerge a rigorous evidence base is required to facilitate clinical adoption and inform the prosthetic approaches to ensure the best functional outcomes for these children. The BEAR PAW provides an accessible, open-source research platform to begin assessing validated outcome measures, refining prosthetic control systems, and examining the degree to which multi-articulating prostheses may make a difference for the users.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

All authors contributed to writing, review, and manuscript preparation activities. MB contributed to the experimental design, development, and fabrication of the research-based pediatric prosthesis. MB and PY performed the experimental data collection. MB and JS performed the data analysis. JS was the principal investigator, provided scientific direction, and performed overall project coordination. WJ provided technical support, guidance, and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frobt.2022.1000159/full#supplementary-material.

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Using robot-assisted stiffness perturbations to evoke aftereffects useful to post-stroke gait rehabilitation

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Stroke is a major global issue, affecting millions every year. When a stroke occurs, survivors are often left with physical disabilities or difficulties, frequently marked by abnormal gait. Post-stroke gait normally presents as one of or a combination of unilaterally shortened step length, decreased dorsiflexion during swing phase, and decreased walking speed. These factors lead to an increased chance of falling and an overall decrease in quality of life due to a reduced ability to locomote quickly and safely under one's own power. Many current rehabilitation techniques fail to show lasting results that suggest the potential for producing permanent changes. As technology has advanced, robot-assisted rehabilitation appears to have a distinct advantage, as the precision and repeatability of such an intervention are not matched by conventional human-administered therapy. The possible role in gait rehabilitation of the Variable Stiffness Treadmill (VST), a unique, robotic treadmill, is further investigated in this paper. The VST is a split-belt treadmill that can reduce the vertical stiffness of one of the belts, while the other belt remains rigid. In this work, we show that the repeated unilateral stiffness perturbations created by this device elicit an aftereffect of increased step length that is seen for over 575 gait cycles with healthy subjects after a single 10-min intervention. These long aftereffects are currently unmatched in the literature according to our knowledge. This step length increase is accompanied by kinematics and muscle activity aftereffects that help explain functional changes and have their own independent value when considering the characteristics of post-stroke gait. These results suggest that repeated unilateral stiffness perturbations could possibly be a useful form of post-stroke gait rehabilitation.

KEYWORDS

rehabilitation, robotics, gait, stroke, aftereffects, adaptation, walking, treadmill

1 Introduction

On average, every 3 seconds, someone in the world has a stroke. Stroke has been a major concern for decades and only appears to be growing in prevalence, as we've seen a 70% increase in stroke cases from 1990 to 2019 (Feigin et al., 2022). A stroke occurs when broken or blocked blood vessels compromise oxygen supply to the brain, which causes death to brain cells. While stroke is indeed an injury to the brain, the death of brain cells can have lasting effects on the whole nervous system and severely impact brain function, speech, and mobility. One of the most common post-stroke issues is gait dysfunction, as an estimated 80% of people lose the ability to walk immediately after having a stroke, and many do not fully regain this ability in the months and years that follow (Duncan et al., 2005). While some disabilities caused by stroke can be fairly common, such as asymmetric gait, it is important to note that stroke is still unique to each individual. Each stroke can affect a different area of the brain, and even a stroke that occurs in the same location has been shown to result in different effects, patient to patient (de Haan et al., 1995; Daly et al., 2010). Because of the prevalence and complexity of stroke, there is much need for robust, patient-specific stroke rehabilitation protocols that allow stroke victims to regain their ability to walk independently and safely.

At a high level, post-stroke gait can usually be characterized by asymmetry. Because stroke often affects just one side of the brain (hemiplegia), one side of the body commonly experiences difficulty in performing motor tasks. Concerning gait, this asymmetry frequently leads to reduced walking speeds (Patterson et al., 2008, 2010), as well as instability and a higher risk of falling (Ugur et al., 2000; Mackintosh et al., 2006). More specifically, post-stroke gait often includes the following behaviors on the affected side: decrease in step length (Titianova et al., 2003), prolonged swing phase (Titianova et al., 2003; Chen et al., 2005; Nadeau, 2014), reduction in overall muscle activity (Olney and Richards, 1996; Chen et al., 2005), prolonged stance phase (Olney and Richards, 1996), less propulsion (Chen et al., 2005), reduced dorsiflexion during swing (Balaban and Tok, 2014), reduced hip and knee flexion during swing (Balaban and Tok, 2014), reduced knee flexion at toe-off (Chen et al., 2005), reduced maximum hip extension (Balaban and Tok, 2014), reduced single support time (Chen et al., 2005), and increased double support time (Nadeau, 2014). For the unaffected leg, common behaviors are: decreased step length (Nadeau, 2014), prolonged stance phase (Olney and Richards, 1996), decreased double support time (Nadeau, 2014), and decreased swing time (Nadeau, 2014).

As stroke is, by definition, an injury to the brain, stroke rehabilitation must consider the brain at some level. One school of thought suggests that to repair the neuronal circuits that are damaged due to cell death during a stroke, repeated and conscious actions are needed to make use of the mechanism of neuroplasticity (Daly and Ruff, 2007; Su et al., 2016). It is believed that through this mechanism, the brain is capable of reorganizing and modifying its structure to allow for better performance and less energy expenditure. The networks in the brain, even throughout adulthood, are not fixed, but instead are always adapting and changing, allowing new tasks to be learned and unused tasks to be forgotten to a degree (Demarin and Morović, 2014). Current theory suggests that for neuroplastic rehabilitation to be most effective, rehabilitation therapy should be repetitive, require focus from the subject, and be similar to the task attempting to be relearned (Daly and Ruff, 2007; Demarin and Morović, 2014; Su et al., 2016).

Robot-assisted post-stroke gait rehabilitation has drawn much interest recently. The inclusion of robotics into the rehabilitation process offers accuracy and repeatability that are not possible with traditional therapy involving clinicians alone (Sale et al., 2012). These robot-assisted strategies have taken on many different forms, ranging from general assistive devices (Peshkin et al., 2005) to body weight supported treadmills (Hesse et al., 1999), to active orthoses (Husemann et al., 2007; Forrester et al., 2011), to full exoskeletons (Nilsson et al., 2014). Overall, these devices have had varying levels of success in terms of post-stroke gait rehabilitation (Hobbs and Artemiadis, 2020).

As discussed above, effective rehabilitation should evoke a neuroplastic response that creates lasting and even permanent changes in a subject's brain. Since permanent and significant neurological changes are not possible at this time after a single therapy session (Reisman et al., 2009), the main initial indicator of an effective post-stroke rehabilitation protocol is the presence of aftereffects. Aftereffects can be defined as changes in behavior that are evoked by an intervention period and carry over to an unperturbed phase that directly follows the intervention. The behavior that is carried over does not need to be similar to the behavior seen during the intervention; it must only be different from the unperturbed phase before the intervention. These aftereffects first show that during the treatment, the brain is learning and adapting. This leads to changes in a subject's performance after the treatment has concluded, demonstrating the brain's ability to make lasting changes with such an intervention. A few studies have shown useful aftereffects toward the goal of post-stroke gait rehabilitation (Reinkensmeyer et al., 2002; Reisman et al., 2009, 2013). One such study (Reisman et al., 2009) produced useful aftereffects with stroke patients using a split-belt treadmill with belts at different speeds. These aftereffects were largely characterized by an increase in step length of up to 5 cm. While this was an impressive result, the aftereffect faded quickly as subjects returned to their baseline behavior after about 25 gait cycles (Reisman et al., 2009). Similar studies using split-belt treadmills have produced similar aftereffects, but have only reported aftereffect durations of a few gait cycles or a few minutes of unperturbed walking (Choi and Bastian, 2007; Huynh et al., 2014). While these studies have used different significance tests, they have all tested for aftereffects using the same general method, comparing post-adaptation gait to baseline gait. Also, these studies tend to focus on the outcome of step length but will occasionally discuss gait cycle timing, kinematics, and muscle activity data. While a useful aftereffect has been achieved in previous studies, much is left to be desired in terms of duration and robustness.

Our lab has developed a novel robotic treadmill that aims to fill the gaps left by previous devices and protocols (Barkan et al., 2014; Skidmore et al., 2015). The Variable Stiffness Treadmill (VST) is a split-belt treadmill capable of varying the vertical stiffness of the interaction between the foot and ground on a single belt (discussed in more detail in **Section 2.2**). In previous studies, the VST has shown great promise toward becoming an effective post-stroke gait rehabilitation device. The unilateral perturbations created on the VST have displayed the ability to evoke interlimb coordination pathways (Skidmore and Artemiadis, 2015, 2016a,b,c,d, 2019). This coordination between legs is vital to human walking and has been suggested to be controlled at a supraspinal level (Seiterle et al., 2015). Additionally, walking on the VST has been directly shown to elicit significant brain activity responses (Skidmore and Artemiadis, 2016c,d). As discussed above, the brain is the root problem of post-stroke gait dysfunction. Therefore, it is believed that considering the brain is a crucial component of stroke rehabilitation protocol design.

A preliminary experiment was run prior to this study to investigate, for the first time, the aftereffects produced on the VST (Chambers and Artemiadis, 2022). In this study, repeated unilateral stiffness perturbations were used as an intervention with eight healthy subjects. These stiffness perturbations resulted in aftereffects that lasted on average over 200 gait cycles and are meaningful to stroke recovery. These aftereffects were an increase to both left and right step lengths, with the unperturbed side (right) increasing significantly more than the perturbed side (left). While this study was a promising pilot investigation, it had a few shortcomings such as the number of subjects, experiment duration, instrumentation, and depth of analysis.

In this paper, we continue and build upon our previous study (Chambers and Artemiadis, 2022) by performing an in-depth investigation of the aftereffects produced by unilateral stiffness perturbations on the Variable Stiffness Treadmill (VST). We show, with a larger subject pool and a longer experiment length, that repeated perturbations can lead to aftereffects lasting up to 575 gait cycles that appear to possibly have strong implications for post-stroke gait rehabilitation. While the aftereffect of asymmetrically increased step length is further confirmed, other aftereffects regarding kinematics, muscle activity, and ground reaction forces are thoroughly examined. The findings of this paper relate directly to the common issues found in post-stroke gait and suggest that the VST could be an extremely useful tool in advancing the field of post-stroke robot-assisted gait rehabilitation.

2 Materials and methods

2.1 Overview

Twelve healthy subjects (5 males and 7 females, age: 24 ± 2.98, all right leg dominant) participated in this study. For the entirety of the experiment, subjects walked on the Variable Stiffness Treadmill (see **Figure 1**). The experiment consisted of 1,300 gait cycles broken into four phases: acclimation, baseline, adaptation, and observation (see **Figure 2**). During the acclimation phase, subjects walked for 50 gait cycles with both belts of the treadmill set to rigid. The purpose of this portion of the experiment was

FIGURE 1
Subject walking on the VST with both belts set to rigid. Reflective markers and EMGs can be seen on the subject, as well as the safety harness.

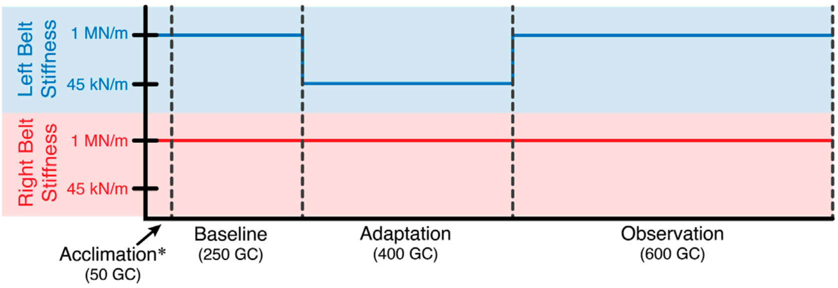

FIGURE 2
Experiment layout in terms of gait cycles. For the entire experiment, the stiffness of the right treadmill belt remained rigid (1 MN/m). The stiffness of the left treadmill belt was reduced to 45 kN/m for the adaptation phase. Otherwise, the left belt stiffness was also rigid.

to allow the subjects to become accustomed to walking on the VST. No data from the acclimation phase was used in the analysis of this study. Next, subjects walked for 250 gait cycles with both sides of the treadmill set to rigid to make up the baseline phase. Unlike the acclimation phase, data from this section of the experiment was used for analysis, as this informed us of each subject's normal walking behavior. Then, in the adaptation phase, subjects walked for 400 gait cycles with the right treadmill belt stiffness set to rigid and the left treadmill belt stiffness reduced to 45 kN/m. This asymmetric environment caused the subjects to adapt and conform to a new way of walking. Lastly, in the observation phase, subjects walked for 600 gait cycles with both belts set to rigid again, just as they were in the baseline phase. The purpose of this phase was to observe what the subject learned and stored, and what aftereffects carried over to unperturbed walking.

During the entire experiment, subjects were able to select a walking speed that felt closest to their normal pace. All subjects had the options of 90, 95, or 100 cm/s. Additionally, all subjects walked in socks to improve force mat readings during walking (see more details below). While walking, subjects were given three options for what to do with their arms. While the subjects were trying different walking speeds they were asked to swing their arms normally while walking. This would be the ideal posture since it is most like normal walking, but unfortunately, most subjects' arms block the cameras from seeing the reflective markers on their hips. As an alternative, subjects were asked to either rest the back of their hands on the handrails or gently hold on to the safety harness straps with only their thumb and index finger. These alternative options were given so each subject could walk as comfortably and confidently as possible without offloading much weight or significantly aiding their balance during the low stiffness perturbations. Nine out of 12 subjects chose the method of gently holding onto the harness, one subject was able to swing their arms normally without blocking any markers, and two subjects rested the backs of their hands on the handrails. Little to no variance was observed between these groups of subjects. Additionally, since all analyses and comparisons presented in this study are within each subject (i.e., no comparison between subjects), these slightly different walking postures between subjects were not seen as a major issue. Lastly, subjects were notified verbally of the last 10 gait cycles in each section of the experiment to inform them of stiffness changes. Informed consent was given, while these experimental protocols are approved by the University of Delaware Institutional Review Board (IRB ID#: 1544521-2).

2.2 Experimental equipment

The primary device used for this study was the Variable Stiffness Treadmill (VST) (Barkan et al., 2014; Skidmore et al., 2015). This robotic device is a split-belt treadmill, where the belts are tied with respect to speed, but not stiffness. The left belt of the treadmill can reduce its stiffness while the right belt remains rigid. The left belt is capable of stiffness levels ranging from 1 MN/m (which is considered rigid) to about 60 N/m (Skidmore et al., 2015). For this experiment, only two stiffness values were used: 1 MN/m and 45 kN/m. While 1 MN/m feels like walking on a typical treadmill, 45 kN/m is comparable to sand or a soft gym mat. The stiffness level of 45 kN/m was selected after performing multiple pilot studies which tested stiffness levels varying from 20 kN/m to 90 kN/m. Stiffness values much lower than 45 kN/m resulted in significant fatigue from the subjects that was visually identifiable. This fatigue seemed to introduce randomness into the data as gait was strenuous and inconsistent. Stiffness levels much higher than 45 kN/m quickly approached a surface that was too similar to the rigid surface of 1 MN/m. This failed to produce substantial differences between sections of the experiment, and the results were often not statistically significant.

Each subject's position in space and its kinematics were collected using a VICON motion capture system. This system includes 8 cameras spaced around the treadmill, each providing data at 100 Hz. Also, 22 reflective markers were placed on each subject's lower body to allow a lower body skeleton to be produced in VICON Nexus, the software used for labeling markers and processing marker data (see **Figure 3**). For this skeleton to be created, the following subject metrics are also required: height, weight, leg length, knee width, and ankle width. Raw marker position data and subject metrics are then used to calculate joint angles at the hips, knees, and ankles using VICON Nexus.

Muscle activity was measured during this experiment with 10 surface electromyographic (EMG) sensors (Trigno, Delsys Inc.). Five EMGs were placed on each leg on the following muscles: tibialis anterior (TA), gastrocnemius (GAS), vastus medialis (VA), rectus femoris (RF), and biceps femoris long head (BF). These five muscles were selected as they help explain movement in all three joints of interest (hip, knee, and ankle) in both directions of flexion and extension. Each subject's skin was prepared by shaving the area (if necessary) and cleaning the area with alcohol wipes. EMGs were attached with double-sided tape and further secured with pre-wrap athletic tape to reduce motion artifact. EMG data were synchronized with motion capture data using a trigger signal from VICON Nexus.

Electromyographic (EMG) data were processed using the following method. For each subject and muscle, the raw data sampled at 2000 Hz was first filtered with a fourth-order Butterworth band-pass filter. Low and high cut-off frequencies of 30 and 300 Hz, respectively, were used. Data were then full-wave rectified. Next, the envelope of the muscle activity data was found by computing a moving average with a window size of 200 data points. Then, a lowpass filter (fourth order, 5 Hz) was used to filter the data again (Shiavi et al., 1998; Singh et al., 2019). The data were then normalized using the maximum value found throughout the experiment. Finally, the EMG data were downsampled to 100 Hz using linear interpolation to match the frequency of the motion capture data. This process produced useful muscle activity data scaled at 0%–100% activity level.

Force mats (Tekscan 3,510 Medical Sensors) were used to collect ground reaction force (GRF) data for the left foot. These mats collect vertical force data in 2068 locations (grid)

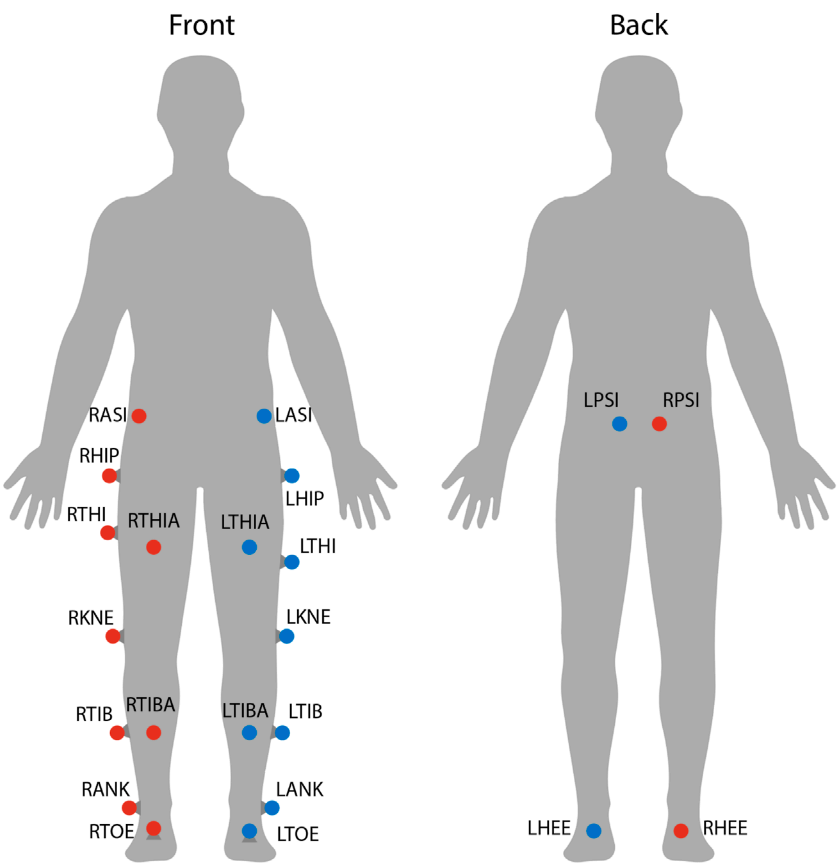

FIGURE 3
Marker locations on each subject. Twenty-two reflective markers were used for motion capture analysis. The center of mass was estimated as the average between LASI, RASI, LPSI, and RSPI markers.

along the walking surface at 100 Hz. From this data, the total force value and center of pressure location were able to be calculated. Additionally, since the GRF position is needed to create a constant, low-stiffness environment, the real-time center of pressure data were used to update the position of the variable stiffness mechanism on the VST. Through preliminary testing of the force mats, it became obvious that different styles of shoes produce significantly different data, even with the same subject. Because of this, subjects walked in socks to improve force mat readings. Force mat data were also synchronized with motion capture and EMG data using a trigger signal from VICON Nexus. Note that GRF data is only available for the left foot as the VST is only equipped with force sensors on the left belt. While the left GRFs were the main interest to us, future experiments will most likely have GRF data for both feet.

Finally, the subjects were wearing a body weight support harness throughout the experiment, but it was only used as a safety precaution. The harness straps were left with a small amount of slack so that none of the subjects' weight was offloaded as this could alter their kinematics and GRF data. The harness was worn by each subject around their torso and did not impede walking in any way (see **Figure 1**).

2.3 Data processing

Each subject's data set, which included marker trajectories, kinematics, muscle activity, and ground reaction forces, was then broken into gait cycles starting at each left heel strike. In other words, a gait cycle was defined from one left heel strike to the next. Heel strike for both legs was detected using a robust kinematic algorithm (Karakasis and Artemiadis, 2021). Then, for each subject, outlier gait cycles were detected using a systematic method that analyzed kinematic data in all three directions at the hip, knee, and ankle, as well as muscle activity data for all 10 muscles (Hobbs and Artemiadis, 2022). Additionally, the last 10 gait cycles of the baseline and adaptation phases were automatically declared as "outliers." This was because the subjects were verbally informed 10 gait cycles before the stiffness of the treadmill was changed. The experiment was designed in this fashion to ensure that subjects were not surprised, but this given information created an anticipatory effect that was not originally desired. For this reason, this section of data was removed. As stated above, the acclimation phase was not involved in any data analysis and will not be discussed any further.

Data were statistically tested to determine significance. The Wilcoxon rank-sum test (non-parametric counterpart to the t-test) was used with the standard α value of 0.05 (Haynes, 2013). This test in particular was chosen as it is non-parametric in nature, and therefore does not make any assumptions regarding the distribution of the data. Because, when investigating aftereffects (discussed below), smaller sample sizes are used, assuming normally distributed data, as the t-test does, would not be appropriate.

The statistical significance of an aftereffect is determined in this study by comparing data from the observation phase to the baseline phase. The baseline phase data were treated as a static complete data set, while the data from the observation phase were tested incrementally. Since the observation phase is defined by its transience, one cannot simply test for significance between the baseline and observation phases in one pass. Therefore, the observation phase must be broken into small sections and tested in groups. After outlier detection was complete, the observation phase length was reduced from 600 to 576 gait cycles. The observation phase was then broken into 23 groups of 25 gait cycles, totaling 575 gait cycles. The last gait cycle (number 576) was simply ignored. The value of 25 was chosen for the group size as it allows for an adequate number of significance tests to be run, while still leaving a sufficient amount of data for each significance test. Each group of 25 gait cycles was then tested for significance against the entire baseline phase. Results of significance testing can be seen in the bottom right of each graph presented in this study, denoted by "$\star\star$". Where the line is present, statistical significance was found. Where the line is not present, no statistical significance was found. Since each of the 23 significance tests is done independently, no line, a solid line, or a "dashed" line can be present. Throughout the analysis, left-tailed, right-tailed, and two-tailed tests were used depending on the specific situation. The type of test that was used is conveyed on each graph above the significance line. An upward-facing arrow indicates that the test was performed against the alternative hypothesis of the observation phase being greater than the baseline phase (right-tailed). A downward-facing arrow indicates that the test was performed against the alternative hypothesis of the observation phase being less than the baseline phase (left-tailed). If no arrow is present, a two-tailed test was performed.

Lastly, for all graphs seen in this study, data were smoothed using second-degree polynomial local regression. This was done using a sliding window of 150 data points and was performed separately for each section of the experiment: baseline, adaptation, and observation. The only purpose of this smoothing is for a more clear visual representation. All significance testing (discussed above) used "unsmoothed" data.

3 Results

In an effort to show that aftereffects are a trend seen in the majority of subjects and not merely in a hand-picked subset, all data analyzed will be a composite of all 12 subjects tested. Therefore, all data is an average over the entire subject pool. Moreover, the main point of this study is to analyze the

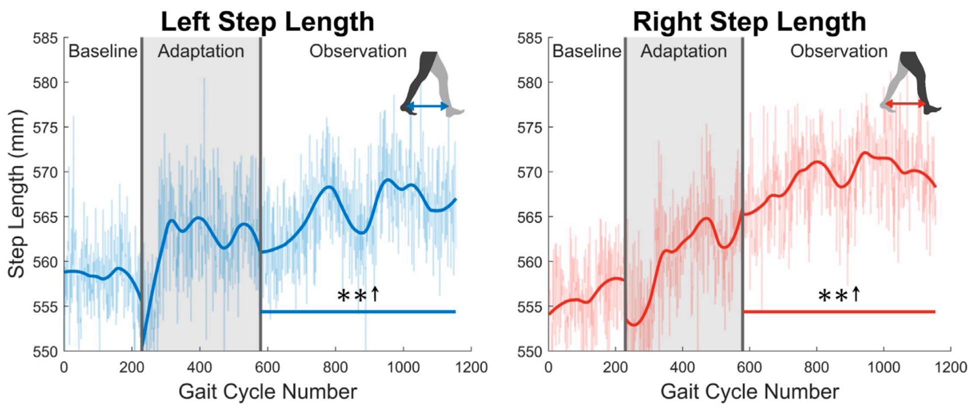

FIGURE 4
Left and right step length averaged for all 12 subjects. Step length was calculated as the projected distance between ankles in the floor plane at the time of heel strike. Both left and right step lengths are statistically significant for the entire observation phase, as indicated by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

aftereffects produced by the perturbations in the adaptation phase. Consequently, we are not focusing on the data in the adaptation phase itself. That data will still, however, be presented in each figure, but will be greyed out in order to draw attention to the baseline and observation phases. Finally, all figures are color coded for added clarity. Blue represents the analysis of the left leg (perturbed side). Red represents the analysis of the right leg (unperturbed side). Purple represents either the analysis of the gait cycle as a whole or the analysis of asymmetry between legs. For asymmetric analysis, the right side parameter is always subtracted from the left.

3.1 Step length

This study shows that repeated unilateral stiffness perturbations on the Variable Stiffness Treadmill (VST) result in long-lasting aftereffects. Many of these aftereffects last for the full observation phase of the experiment (575 gait cycles) and appear to directly work toward correcting common issues seen in post-stroke gait dysfunction, like those discussed in Section 1. This will be examined further in Section 4.1.

At the highest level, meaningful aftereffects can be seen in terms of step length (see Figure 4). Step length in this study was measured as the Euclidean distance of the projection of the ankle markers of each leg onto the treadmill surface plane, at heel strike. For example, left step length is the distance between ankle markers at left heel strike, and *vice versa*. For the left leg, a statistically significant increase is seen when the observation phase is compared to the baseline phase, lasting for the entire observation phase. This increase has an average magnitude of 7.07 mm (1.27%). The right side is also significantly increased for the entire observation phase, but with an average magnitude of 13.07 mm (2.35%). It should be noted that, while the right leg is the unperturbed leg, it displays the larger step length increase. The asymmetry between left and right step lengths is also significant for the entire observation phase (see Figure 5).

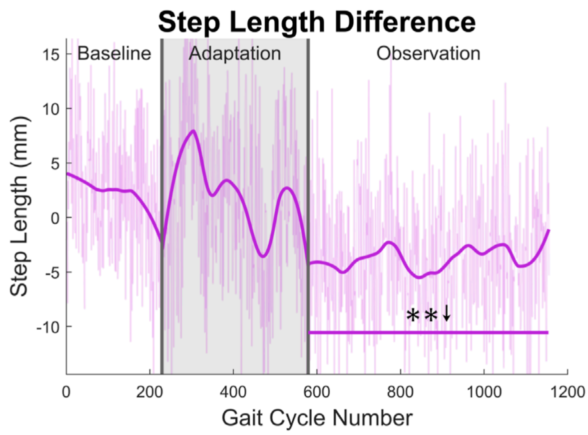

FIGURE 5
Step length asymmetry averaged for all 12 subjects. Step length was calculated as the projected distance between ankles in the floor plane at the time of heel strike. For this figure, step length asymmetry was found by subtracting right step length from left step length. The right step length is significantly greater for the entire observation phase, as indicated by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

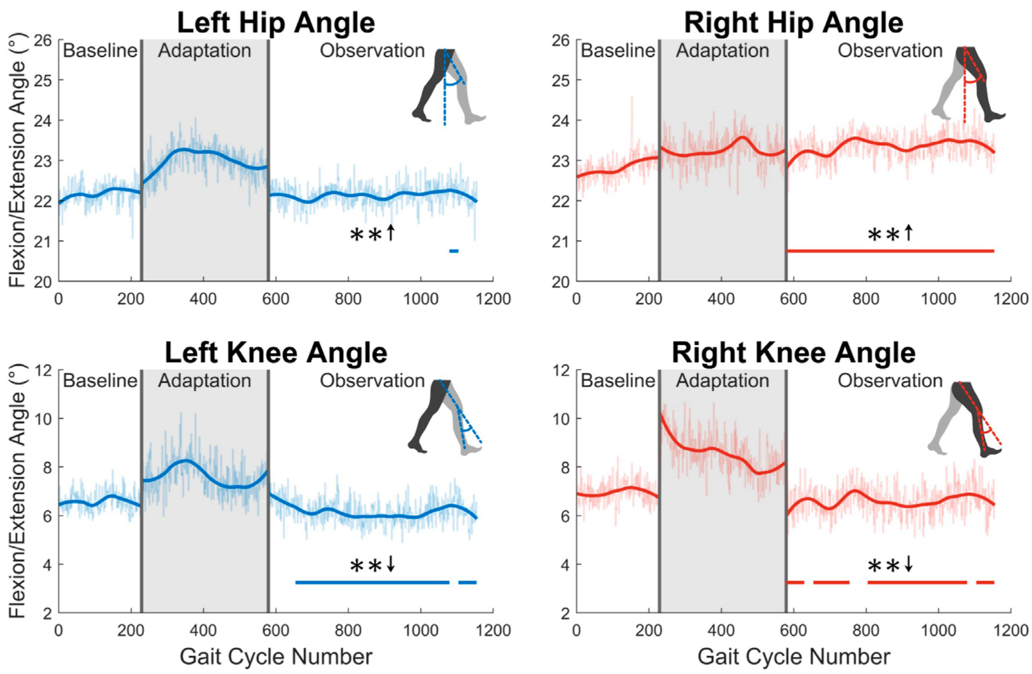

FIGURE 6
Hip and knee flexion/extension angles at heel strike for both left and right sides. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

3.2 Kinematics and kinetics

First, joint kinematics at heel strike will be examined. The left hip does not significantly increase its flexion angle at heel strike, as only one group of 23 was statistically significantly increased. The right hip flexion angle at heel strike however was significantly increased for the entire observation phase (see Figure 6). At the knee, a significant decrease in flexion is seen at heel strike for both left and right legs (see Figure 6). Both of these show statistically significant results for 83% of the observation phase.

Second, the trailing leg will be examined by considering the maximum hip extension angle created throughout the gait cycle (see Figure 7). The maximum extension angle (or minimum flexion-extension angle) made by the left leg is significant for nearly the entire observation phase (91%). The right leg however only shows significance for 35% of the observation phase.

Next, the knee joint is more closely examined. As shown in the top two graphs in Figure 8, subjects showed increased maximum knee flexion during the swing phase. This trend was statistically significant for the entire observation phase for both legs. Additionally, as shown in the bottom two graph in Figure 8, subjects increased their knee flexion angle at toe-off. This increase was statistically significant for the entire observation phase for the right leg, and nearly the entire observation phase for the left leg (96%).

Fourth, joint velocities during the swing phase were analyzed (see Figure 9). A significant increase in maximum flexion angular velocity is seen for a majority of the observation phase at both the left hip (70%) and the right hip (96%). For the knee, an increase in maximum extension angular velocity is seen for the entire observation phase for both legs (see Figure 9).

Next, the ground reaction force (GRF) was examined. While the GRF was only available for the left leg due to hardware limitations, the trend of increased push-off force was observed for the entire observation phase (see Figure 10). The magnitude of this increase was quite notable at an average of 16.87% when comparing the observation phase to the baseline phase. This push-off force was defined as the second peak in the GRF curve during stance phase. The process ensured that push-off force was being analyzed and not heel strike force.

3.3 Muscle activity

In this section, muscle activity will only be discussed during the swing phase. This is where muscles can most easily be related to kinematics and step length, as will be discussed in Section 4.

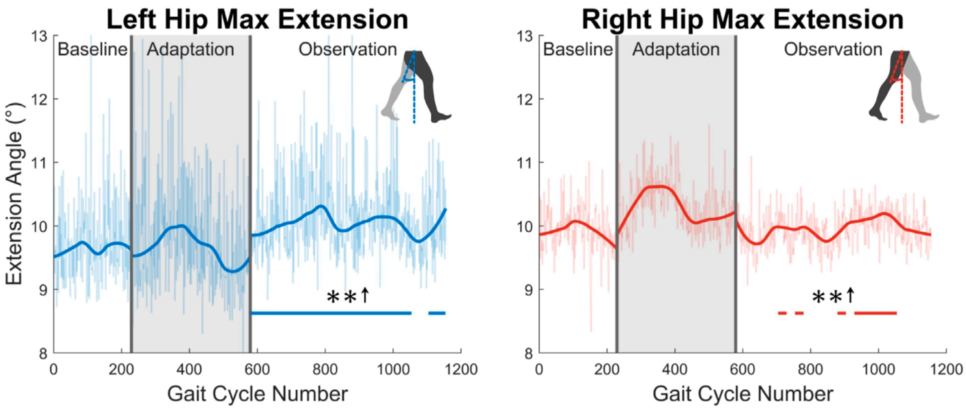

FIGURE 7
Maximum hip extension throughout the gait cycle for left and right legs. Note that values are positive because the extension angle was used instead of the flexion/extension angle for this figure. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

The average activity level during the swing phase of all 10 muscles measured can be seen in Figure 11. Starting with the tibialis anterior (TA), significance can only be seen for part of the observation phase for both the left leg (48%) and the right leg (43%). Next, the gastrocnemius (GA) shows a statistically significant increase in the left leg for 65% of the observation phase. A significant increase is seen for 22 out of 23 (96%) of the observation groups for the right leg. For the vastus medialis (VA), significance is seen for part of the observation phase for both the left (65%) and right (57%) sides. Next, a significant increase is seen in the left rectus femoris (RF) for the entire observation phase. This can be observed to a lesser degree on the right side, as only 70% of the groups were statistically significant. Similarly, a reduction in biceps femoris (BF) activation is seen more clearly on the left side (100%) than on the right side (48%).

3.4 Gait cycle timing

The gait cycle can also be analyzed temporally. First, and most simply, gait cycle length (with respect to time), can be measured by finding the elapsed time between left heel strikes. A significant increase can be seen for the entire observation phase (see Figure 12).

Next, the gait cycle can be more deeply analyzed by examining how long (in terms of percentage) the subjects spent in each section of the gait cycle (see Figure 13). First, for swing phase, a significant decrease for a majority of the observation phase can be seen in both the left side (91%) and the right side (96%). As expected, the exact opposite trend is seen in the stance phase for both legs. Next, significant decreases can be seen in the left single support phase (96%) and right single support phase (91%). Predictably, the left and right double support phases show the opposite trend with similar levels of significance (100% for the left side, 74% for the right side). While it is not displayed graphically, the same analysis was performed in terms of time instead of percentage. The results for stance and double support were nearly identical to those seen in Figure 13, and the results for swing and single support were largely insignificant.

From Figure 13 and the discussion above, it would appear that there is not any significant asymmetry in terms of gait cycle timing. This can be further confirmed by investigating more directly the asymmetry with respect to swing and stance (see Figure 14). Swing time asymmetry was calculated for each gait cycle by subtracting the time the right leg spent in the swing phase from the time the left leg spent in the swing phase. For stance time asymmetry, the same method was used. Significance is only found in 1 out of 23 groups (4%) for both swing time asymmetry and stance time asymmetry.

4 Discussion

The results of this study suggest that the Variable Stiffness Treadmill (VST), *via* its unilateral low stiffness perturbations, could be a very useful tool with respect to post-stroke gait rehabilitation. This section will dive further into stroke rehabilitation, mention the shortcomings of this study, and contemplate future applications of the results presented in this paper.

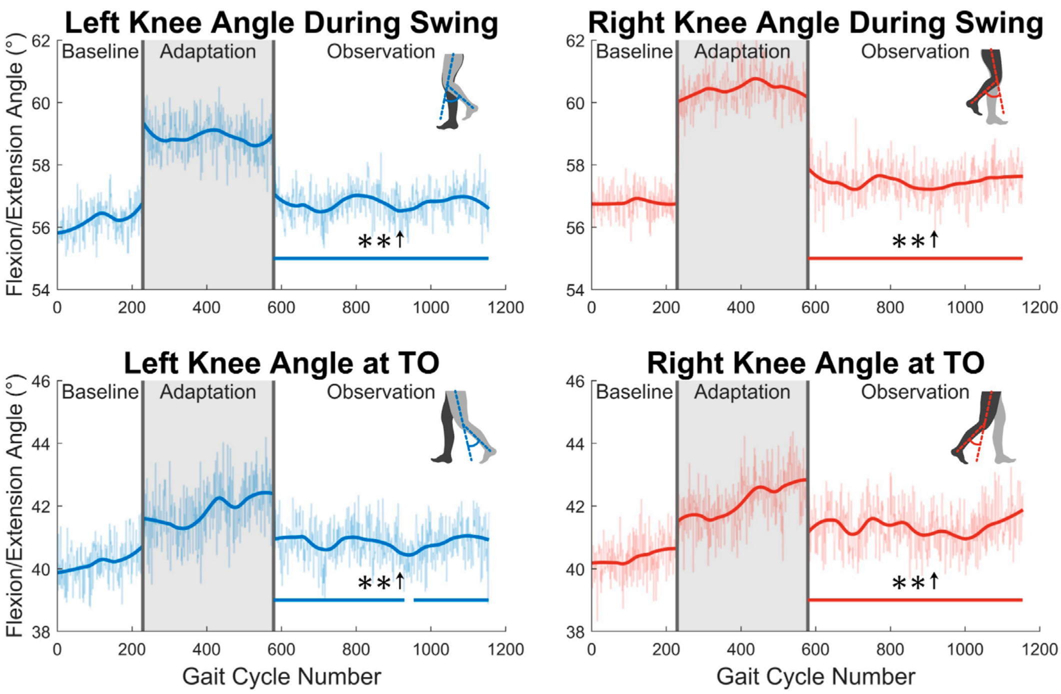

FIGURE 8
The top two graphs display maximum left and right knee flexion/extension angle during the swing phase. The bottom two graphs show knee flexion/extension angle at the instant that toe-off occurs. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

4.1 Stroke rehabilitation

The VST shows the potential to be instrumental in post-stroke gait rehabilitation, as it produces long-lasting aftereffects after a single 10-min intervention. The asymmetric environment this device creates appears to engage subjects in a unique way. It is important to note that many of the aftereffects analyzed last for the entire observation phase of the experiment (575 gait cycles). With only 400 perturbed gait cycles, the length of this aftereffect is quite substantial, and to our knowledge has not been shown before. Additionally, the aftereffects for many parameters analyzed (step length included) only ended due to the length of the experiment. While we currently do not know the true duration of these aftereffects, it is possible that they continue for many more gait cycles beyond the duration of this study.

As was discussed in **Section 1**, post-stroke gait is often characterized first by step length asymmetry and an overall decrease in step length on both sides (Titianova et al., 2003; Nadeau, 2014). The aftereffect of asymmetrical step length increase seen in this study directly counteracts said issue. The argument can be made that because step length is measured from ankle to ankle, it is dependent on the trailing leg as much as the leading leg. Therefore, this increase in step length could simply be caused by each subject's trailing leg "riding" the treadmill for longer. While this theoretically could be the case, this theory can be disproven by investigating step length in a different fashion or looking at a different variable. Analyzing the distance from the leading foot to the center of mass, which we'll call anterior step length, shows that subjects are in fact placing their leading foot farther in front of their center of mass (see **Figure 15**). A significant increase in anterior step length is seen for the entire observation phase. More explicitly, anterior step length is measured as the anterior/posterior distance between the center of mass and the leading heel at heel strike. As only the lower body was tracked during this study, the center of mass is estimated as the average position of the following four markers around the hips: left anterior superior iliac, right anterior superior iliac, left posterior superior iliac, and right posterior superior iliac (see **Figure 3**). This analysis suggests that the step length aftereffects produced by unilateral stiffness perturbations on the VST are in part caused by swinging the leg farther forward prior to heel strike. This appears to relate to the behavior seen in subjects post-stroke (Hirata et al., 2019).

While step length and step length asymmetry characterize post-stroke gait at the broadest level, kinematics can help explain the cause of such gait and how it can be corrected. The kinematic results analyzed in **Section 3.2** both support and help explain

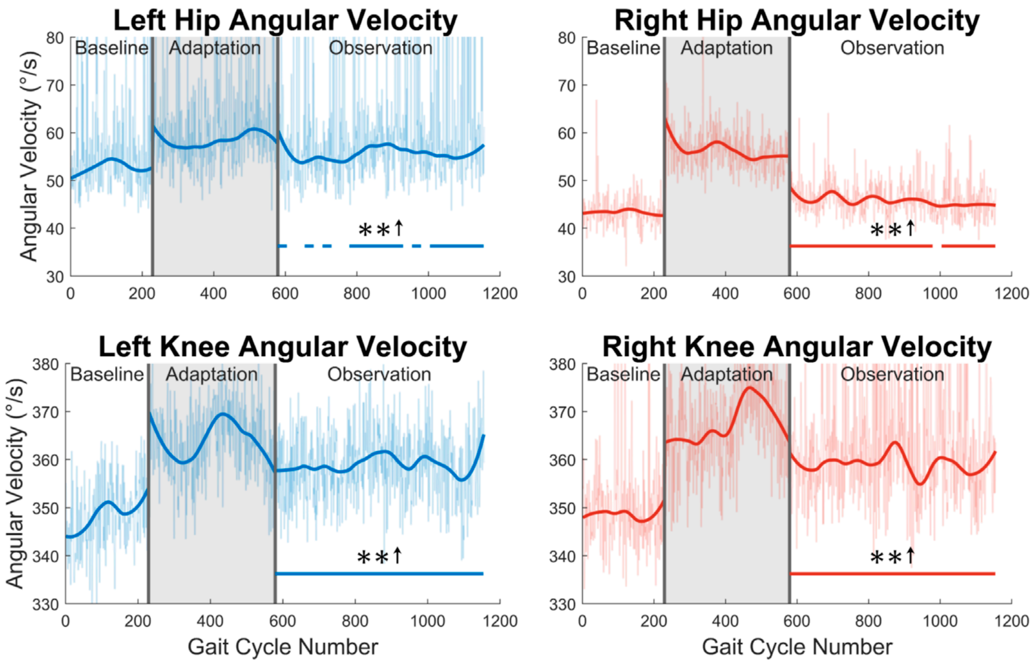

FIGURE 9
Maximum hip and knee angular velocities during the swing phase for both left and right legs. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

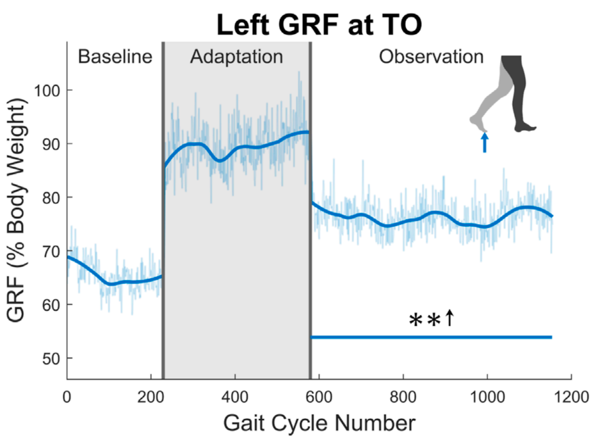

FIGURE 10
Maximum vertical ground reaction force between midstance and toe-off for the left leg in percent body weight. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

the observed step length aftereffects as well as address more specific kinematic issues commonly found in post-stroke gait as discussed in Section 1. We can see that this step length increase is explained kinematically first by increased hip flexion. Reduced hip flexion during the swing phase is a quite common behavior post-stroke and may be a major reason for the asymmetric step length that is often seen (Balaban and Tok, 2014). The results of this study seem to directly counteract this behavior. Recalling that the right leg produced the larger step length during the observation phase, this behavior can at least be explained in part by the right hip having an increased level of flexion when the right heel made initial contact. While for the hip, more flexion at heel strike helps produces a larger step length, more extension is required at the knee to assist in increasing step length. Since there is less flexion at the knee joint, the foot can be placed farther in front of the subject's center of mass at heel strike, again aiding in explaining how an increase in step length is achieved. Another common post-stroke trend is reduced hip extension during the stance phase when approaching push-off (Balaban and Tok, 2014). Not only does this reduce overall step length, but also limits the amount of forward propulsion that can be generated during terminal stance. The aftereffect of increased

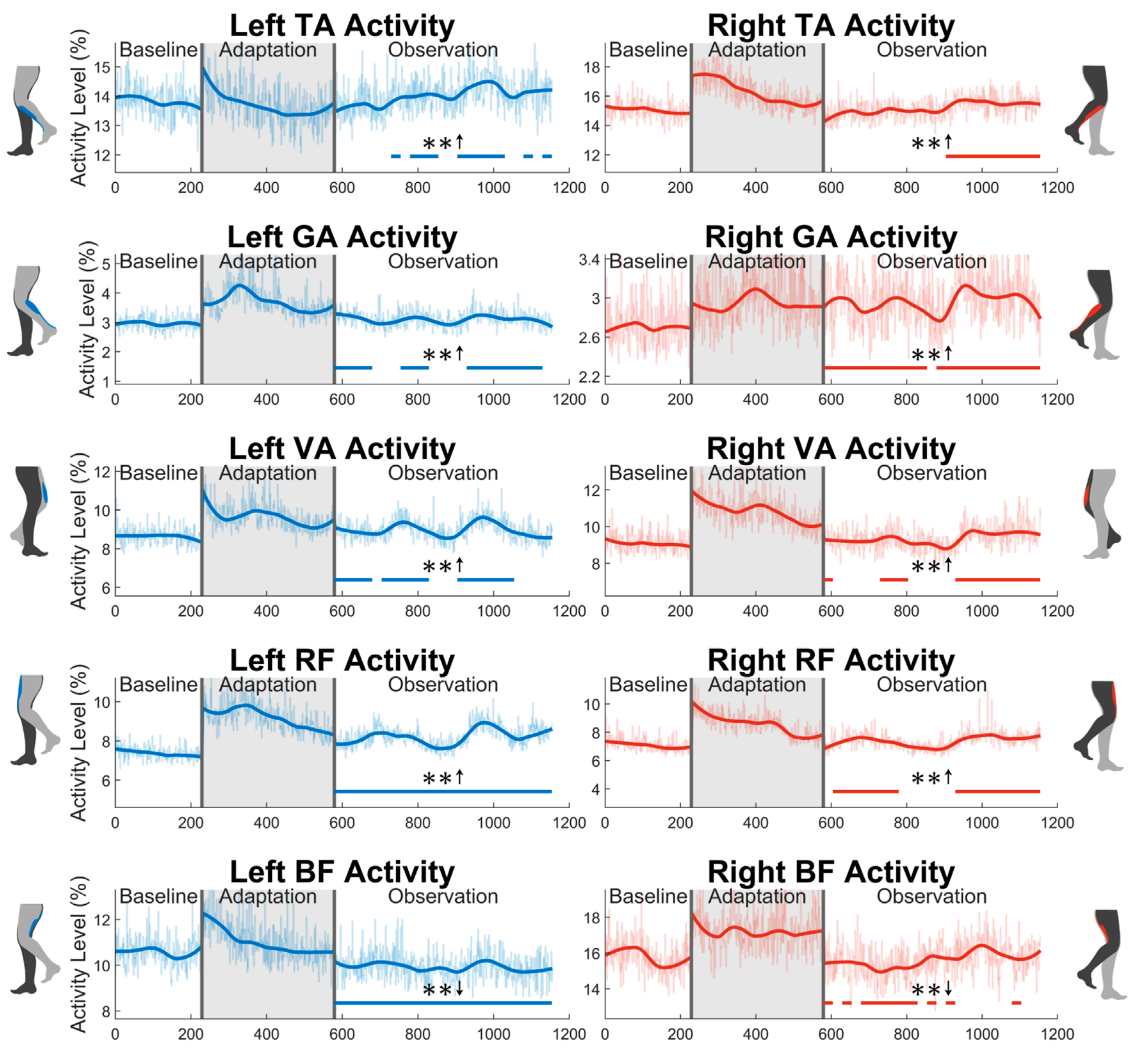

FIGURE 11
Average muscle activity during swing phase for all 10 muscles measured in this study: tibialis anterior, gastrocnemius, vastus medialis, rectus femoris, and biceps femoris. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

max hip extension during stance seen in this study again appears to directly work toward correcting common post-stroke gait dysfunction behavior.

Looking more closely at the knee joint, an aftereffect of higher maximum flexion during swing is seen. For a larger step length to be achieved, the leg must travel more distance during the swing phase. One way that humans maximize step length while keeping energy expenditure low is by reducing the moment of inertia of the swing leg. This is most commonly achieved by flexing the knee more during the swing phase (Smith and Hanley, 2013). Additionally, this higher knee flexion during swing appears to directly counteract the common post-stroke trend of more knee extension during the swing phase (Balaban and Tok, 2014). This post-stroke trend is thought to be at least partially responsible for foot drop (or toe drag), which is known to be a major cause of falling (Little et al., 2014; Matsuda et al., 2017). The aftereffect of increased knee flexion could be beneficial in creating enough clearance between the ground and the swing foot to avoid tripping. Next, an aftereffect of increased knee flexion at toe-off was observed for both left and right legs. The reason for this behavior is not quite as clear. It is possible that subjects were simply preparing for the increased maximum flexion angle that was about to be achieved during the ensuing swing phase. It is also feasible that increased knee flexion at toe-off indicates an early transfer of weight to the front leg in preparation for faster walking or increased step lengths. This trend is meaningful

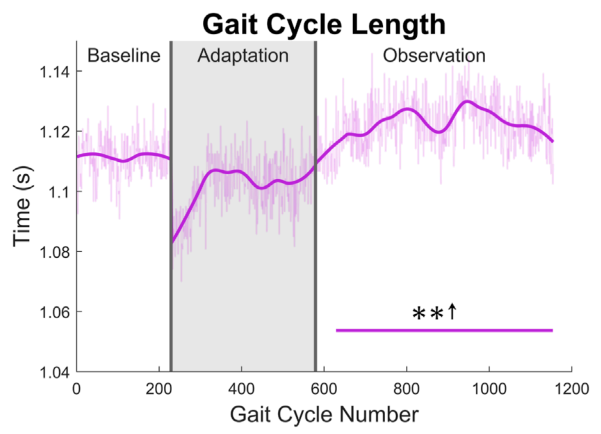

FIGURE 12
Gait cycle length with respect to time (measured from left heel strike to left heel strike). Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

though, as reduced knee flexion is a common behavior in post-stroke gait (Chen et al., 2005). While the exact connection between increased knee flexion at toe-off and larger step length is not known for certain, this behavior appears to be promising in terms of post-stroke gait rehabilitation. In terms of kinematics, the last parameters to discuss are the angular velocities at the hip and knee joints during the swing phase. While, to our knowledge, these have not been investigated in stroke subjects to the same degree as the other parameters discussed, simply considering the dynamics of the swing leg can provide insight into why joint velocities are so important. First, another mode of generating a larger step length is increasing the momentum of the swing leg. Simply put, if the leg is moving at a higher speed during swing phase, a larger step can more easily be achieved. Examining the maximum angular velocity of the hip and knee during swing gives insight into this idea. Both an increase in hip flexion speed and knee extension speed add momentum to the swing leg and allow it to be swung farther forward prior to heel strike. Also, since increased walking speed is a major goal of post-stroke gait rehabilitation (Patterson et al., 2008, 2010), consider how joint speed impacts walking speed. Flexing the hip and extending the knee at a faster rate during swing allows for gait speed to be increased through two distinct modes: increasing step frequency while holding step length constant or increasing step length while holding step frequency constant. While these other parameters (increased step length and increased step frequency) *may* be accompanied by an increased walking speed, they are not as directly related to walking speed as joint speed is.

Aside from kinematics, the ground reaction forces help explain the larger step lengths and again seem to work toward correcting the common post-stroke issue of reduced propulsion (Chen et al., 2005). Simply put, pushing off the ground with more force will allow the leg to be swung faster and farther forward, resulting in a larger step length. It is important to note that the ground reaction forces captured in this study are solely in the vertical direction. While this is not the total propulsion force that is presented in other gait studies, the vertical force is related to the total force through simple geometry. Interestingly enough, the larger vertical forces were seen when a larger amount of hip extension was taking place in terminal stance. Assuming that, as hip extension increases, the push-off force becomes more in the horizontal direction, one would think that the vertical ground reaction force read on the VST would decrease. The fact that this force actually increases, suggests that the true propulsion force aftereffect is significantly greater than what is presented in this paper.

Concerning muscle activity, many of the muscles observed in this study help explain the increased step length, as was discussed in **Section 3.3**. The TA in particular is of great importance for post-stroke gait rehabilitation. One of the most common issues in post-stroke gait is reduced dorsiflexion during swing (Balaban and Tok, 2014). This behavior can lead to toe drag (Von Schroeder et al., 1995), which is one of the most common modes of falling in stroke victims. A slight aftereffect of increased TA activation was seen in this study. An increase in TA activity during the swing phase could be one factor that allows for more ankle dorsiflexion, increasing the clearance level between the foot and ground Intiso et al. (1994); Westhout et al. (2007). Even though an increase in TA activity was seen, it was not accompanied by an increase in dorsiflexion in the healthy subjects who participated in this study. It is feasible that, due to joint limitations, a significant increase in dorsiflexion cannot be achieved in individuals who already dorsiflex a healthy amount, but this is merely speculation. This will need to be further tested with more healthy individuals and stroke victims to be able to discuss this topic with more confidence. Moving past the TA, the GA assists in knee flexion. It is presumed that the increased activation seen helps explain the changes in knee flexion discussed in **Section 3.2** to a degree. Next, the increase in VA activity can help describe the increase in knee extension speed also discussed in **Section 3.2**. For the RF, an increase in activity can assist in explaining the increase in hip flexion that helped generate the increase in step length. Next, a reduction in BF activation can assist in explaining the increased hip flexion discussed in **Section 3.2**. Noting that the BF is a hip extensor, a decrease in its activity may allow for more hip flexion *via* the hip flexors, such as the RF. It is difficult to identify further specific common post-stroke gait muscle activity behaviors to relate to the concepts just discussed. While dysfunction in muscle activity is certainly present

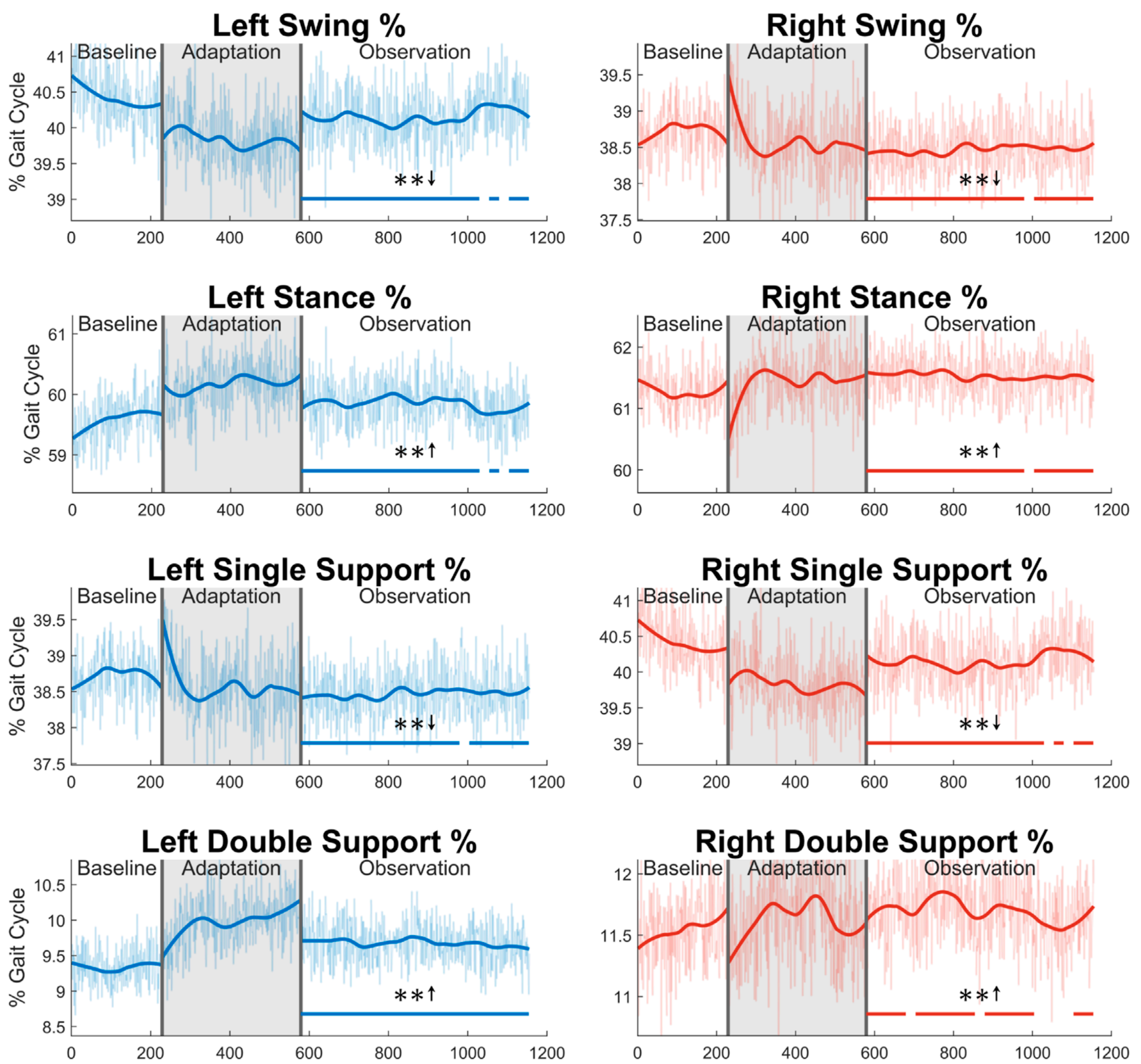

FIGURE 13
Sections of the gait cycle displayed with respect to how much of the entire gait cycle they occupy (in terms of percentage). The double support phase is determined to be left or right depending on which foot is in front and has more recently achieved heel strike. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

post-stroke, specific behaviors vary considerably from subject to subject (Den Otter et al., 2007; Daly et al., 2010). In general, a reduction of overall muscle activity is commonly seen with stroke subjects, especially on the paretic side of their body (Olney and Richards, 1996; Chen et al., 2005). While only a small set of muscles were analyzed in this study, a general aftereffect trend of increased muscle activity is seen. On both the left and right sides, 80% of the observed muscles were significantly increased for at least half of the observation phase. While an experiment measuring more muscles would need to be performed to say this more confidently, the results presented here are at a minimum trending in the correct direction.

Concerning gait cycle timing, it most likely does not help to understand function changes, such as increased step length, but is more likely a result of such changes. This can be seen clearly when examining gait cycle length with respect to time. The increase seen appears to be directly linked to the step length increase observed. As subjects are walking at a fixed speed on the treadmill, for larger steps to be taken, the gait cycle needs to be accomplished over a longer period. Otherwise, the subject would begin to walk faster than the treadmill belts are moving. Gait cycle timing parameters do, however, help characterize and differentiate between healthy and post-stroke gait. Additionally, the gait cycle

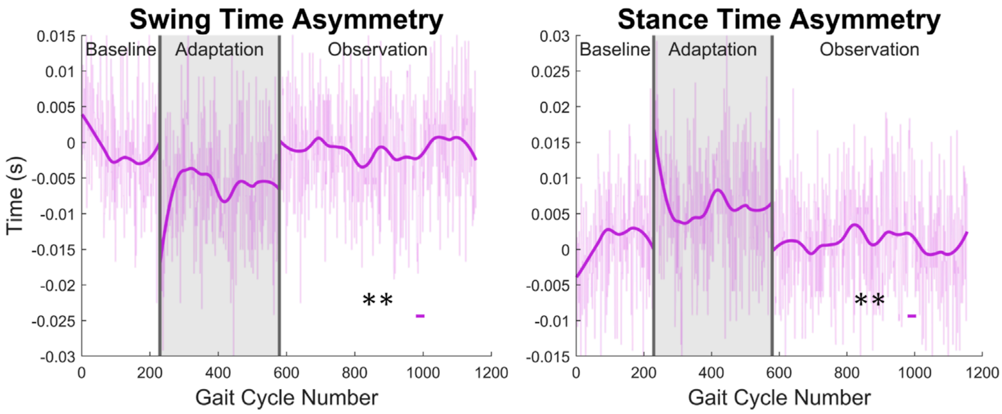

FIGURE 14
Swing and stance time asymmetry in terms of time. For the swing phase, asymmetry was found by subtracting the time spent in right swing from the time spent in left swing. For the stance phase, the same process was used. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

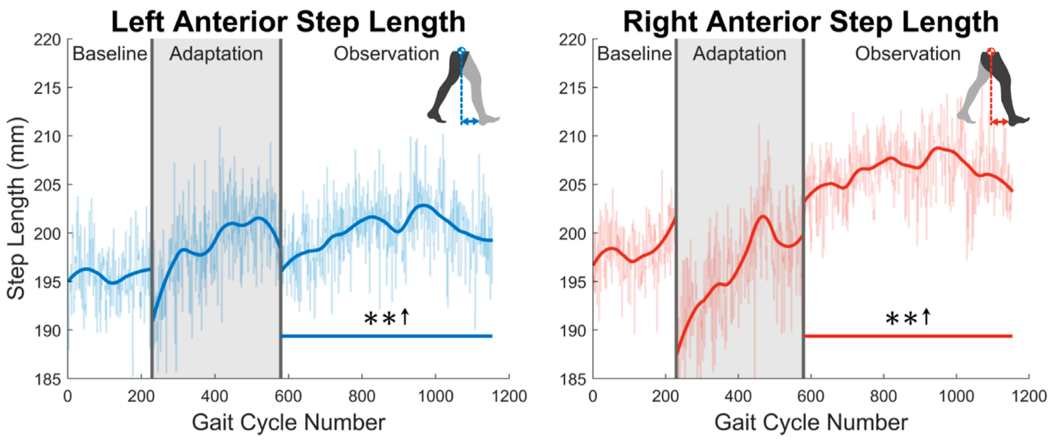

FIGURE 15
Left and right anterior step length averaged for all 12 subjects. Anterior step length was calculated as the anterior/posterior distance between the center of mass and the leading heel at heel strike. Significance is shown in the observation phase as compared to the baseline phase by the significance line. All significance testing was performed on "unsmoothed" data (seen in the lighter line). The darker line is the data smoothed by 2nd-degree polynomial local regression and was added only to allow the reader to more clearly see trends in the data.

timing data presented in this study only appears to work toward correcting common post-stroke gait issues to a small degree. While a few specific behaviors, such as a prolonged swing phase (Titianova et al., 2003; Chen et al., 2005; Nadeau, 2014) and decreased double support time (Nadeau, 2014), do appear to be corrected by our findings, many other issues are not properly addressed. It is possible that these results could improve with subjects whose gait is already asymmetric, but this would require future investigation. These limitations will be further discussed in the next section.

While there are many significant aftereffects presented in this study, we must question whether or not they are useful to stroke rehabilitation. It has been debated whether or not these short-term aftereffects in healthy subjects are genuine indicators of the possibility of long-term, neuroplastic, functional changes in stroke subjects (Reinkensmeyer and Patton, 2009; Huang et al., 2011). First, when comparing stroke subjects with healthy subjects, multiple studies have shown that asymmetric gait training translates to both populations in a similar fashion after a single therapy session (Reisman et al., 2005, 2007, 2009). This comparison has been previously investigated using age-matched and gender-matched healthy control subjects. One study even notes a more robust aftereffect in the post-stroke subjects than in the healthy subjects (Reisman et al., 2009).

Second, the topic of creating long-lasting effects must be considered. While this topic has yet to be thoroughly explored, one study suggests that transient aftereffects can be capitalized on through a regimented training program (Reisman et al., 2013). This study showed that through repeated error augmentation therapy sessions with stroke patients, trends of step length asymmetry improvements were evident at both 1-month and 3-month check-ins periods (Reisman et al., 2013). While this environment of unmatched belt speeds differs from the unilateral stiffness perturbations performed in our study, both environments are asymmetric in their nature and resulting functional changes. We are hoping that these seemingly useful aftereffects can be effective in creating long-term corrective outcomes. As mentioned in **Section 4.3**, this protocol will first need to be tested with stroke patients through a single therapy session, and then eventually through a repetitive training program.

4.2 Shortcomings

While the data presented in this study is indeed quite promising, the study did have its limitations. Regarding the experimental design, first, the observation phase of the experiment is not long enough to capture many of the aftereffects in their entirety. While this is in one sense good news, because long-lasting aftereffects are the goal, having a fuller understanding of the duration would be beneficial. Next, only having access to ground reaction forces on one side of the treadmill leaves many questions unanswered. The results obtained from the left side were quite encouraging, but having access to both sides would allow for a deeper analysis and understanding of human gait in this environment. Finally, while this experiment was not designed to explain different stiffness levels, simply treating 45 kN/m as "low stiffness" and 1 MN/m as "high stiffness" raises many questions in terms of stiffness level. At this point, we do not have a good understanding of how different stiffness levels would affect human gait aftereffects.

With respect to the results of the experiment, most of the shortcomings are related to gait cycle timing (discussed in **Section 3.4**), as this is what many of the common post-stroke behaviors discussed in **Section 1** refer to. Several of these behaviors were either not improved by the results presented, or the results work in a counteractive way. Some examples of these trends seen in stroke patients are the following: prolonged swing phase (Titianova et al., 2003; Chen et al., 2005; Nadeau, 2014), reduced single support time (Chen et al., 2005), and increased double support time (Nadeau, 2014) for the affected leg, and prolonged stance phase (Olney and Richards, 1996) and decreased swing time (Nadeau, 2014) for the unaffected leg. While we believe that the results, as a whole, presented in this paper greatly outweigh the shortcomings addressed here, they are important to note for future study and experiment design.

4.3 Implications and future applications

This study is quite encouraging in the field of robot-assisted post-stroke gait rehabilitation. The aftereffects found after a single walking session are unmatched in the literature according to our knowledge. We hope that this study helps lead to patient-specific repeated interventions that treat each stroke subject based on their individual needs.

We hope to accomplish this by first gaining a fuller understanding of the perturbations created on the VST. This could be accomplished first by performing similar experiments with varying stiffness levels and section duration. Additionally, having a smaller subset of subjects come back regularly for VST interventions could help us understand the longer-term effects of repeated unilateral stiffness perturbations and how they could be used in a clinical setting. Another great future step would be to test the same, or a similar protocol, with a subject pool of stroke patients. While the results are promising with healthy subjects, we hope to soon reproduce these results with stroke patients.

Finally, and possibly most importantly, we believe that modeling this behavior is an integral part of the process of creating an effective post-stroke gait rehabilitation protocol. As was discussed in **Section 4.1**, the issues presented with stroke are unique to every stroke case. Therefore, to have a truly robust rehabilitation process, we must not "paint with broad strokes," but be able to meet each subject's specific needs. Such a complex issue requires a robust model that can simulate an individual's behaviors and dysfunction and then solve for the best possible mode of intervention. While progress is being made in this area (Chambers and Artemiadis, 2021), further research and more studies are required.

Currently, the results presented and discussed in this paper show much promise toward achieving the future goal of a robust, post-stroke gait rehabilitation protocol. This study suggests that the unilateral stiffness perturbations created on the Variable Stiffness Treadmill may be able to assist in correcting many of the problems generally seen in gait post-stroke. We show a significant, asymmetric increase in step length that lasts at least 575 gait cycles, which is supported by kinematics, kinetics, muscle activity, and gait timing data. Based on these results, we believe the main contribution of this paper is a deeper analysis of a promising therapy protocol that is achieved using our unique robotic treadmill. We hope that extensions of this study will drastically improve the landscape of post-stroke gait rehabilitation in the future.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by University of Delaware Institutional Review Board (IRB ID#: 1544521-2). The patients/participants provided their written informed consent to participate in this study.

Author contributions

VC and PA contributed to the conception and design of the study. VC performed the experiments, analyzed the data, and wrote the first draft of the manuscript. VC and PA contributed to the manuscript revision, and read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Feasibility, coverage, and inter-rater reliability of the assessment of therapeutic interaction by a humanoid robot providing arm rehabilitation to stroke survivors using the instrument THER-I-ACT

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Objective: The instrument THERapy-related InterACTion (THER-I-ACT) was developed to document therapeutic interactions comprehensively in the human therapist–patient setting. Here, we investigate whether the instrument can also reliably be used to characterise therapeutic interactions when a digital system with a humanoid robot as a therapeutic assistant is used.

Methods: *Participants and therapy:* Seventeen stroke survivors receiving arm rehabilitation (i.e., arm basis training (ABT) for moderate-to-severe arm paresis [n = 9] or arm ability training (AAT) for mild arm paresis [n = 8]) using the digital therapy system E-BRAiN over a course of nine sessions. *Analysis of the therapeutic interaction:* A total of 34 therapy sessions were videotaped. All therapeutic interactions provided by the humanoid robot during the first and the last (9th) session of daily training were documented both in terms of their frequency and time used for that type of interaction using THER-I-ACT. Any additional therapeutic interaction spontaneously given by the supervising staff or a human helper providing physical assistance (ABT only) was also documented. All ratings were performed by two trained independent raters.

Statistical analyses: Intraclass correlation coefficients (ICCs) were calculated for the frequency of occurrence and time used for each category of interaction observed.

Results: Therapeutic interactions could comprehensively be documented and were observed across the dimensions provision of information, feedback, and bond-related interactions. ICCs for therapeutic interaction category assessments from 34 therapy sessions by two independent raters were high (ICC ≥0.90) for almost all categories of the therapeutic interaction observed, both for the occurrence frequency and time used for categories of therapeutic interactions, and both for the therapeutic interaction performed by the robot and, even though much less frequently observed, additional spontaneous therapeutic interactions by the supervisory staff and a helper being present. The ICC was similarly high for an overall subjective rating of the concentration and engagement of patients (0.87).

Conclusion: Therapeutic interactions can comprehensively and reliably be documented by trained raters using the instrument THER-I-ACT not only in the traditional patient–therapist setting, as previously shown, but also in a digital therapy setting with a humanoid robot as the therapeutic agent and for more complex therapeutic settings with more than one therapeutic agent being present.

KEYWORDS

robot, arm, stroke, interaction, social, reliability, rater, rehabilitation

1 Introduction

While neuro-disabilities including those that are stroke-related are on the rise globally (Nguyen et al., 2019), neurorehabilitation at the same time offers treatment to combat disabilities (Stroke Units Trialist Collaboration, 2013; Langhorne and Ramachandra, 2020) to a large degree by therapeutic training that promotes functional recovery, i.e., "neural repair therapy" (Joy and Carmichael, 2021), based on mechanisms of brain plasticity (Kane and Ward, 2021). Such restorative therapy frequently implies a prolonged intensive and specific training, led by therapists. Such training therapy intends to achieve goals related to functional recovery that promotes a patient's capacities for everyday life activities and, consecutively, participation in social life. To achieve such goals, the process of therapy itself, i.e., during therapeutic sessions, needs to be appropriately structured to enable a patient to perform the specifically chosen type of ("neural repair") training in an engaged and committed way, frequently over extended periods of time (Michael et al., 2020).

As patients are not experts in such trainings, therapists need to provide information, e.g., training specifications and instructions, and provide feedback that matches the focus of the training, e.g., knowledge of the performance, information about how the training task was realised with one's body or knowledge of the result, the measurable result of the training behaviour such as time and precision. In addition, therapists promote a positive and enduring work alliance by taking interest in the other person, responding to their needs, or, at times, by introducing their own personal experiences and alike. All these activities can be referred to as therapeutic interactions. Together, they can be regarded critical for training therapy to meet its process goals and, hence, are of great interest in rehabilitation research.

For a long time, however, no validated tools were available to comprehensively assess therapeutic interactions until recently, when the instrument THER-I-ACT was specifically constructed to assess a therapeutic interaction (Platz et al., 2021). The types of therapeutic interactions covered by THER-I-ACT include various categories of information provision (e.g., goal-related interactions, training specifications, and instructions), feedback (e.g., knowledge of performance or result and added social stimuli), and bond-related interactions (e.g., showing interest in the other person, responsivity to cues provided by the interaction partner, and solving conflicts). THER-I-ACT promotes a reliable manual-based assessment of these therapeutic interactions both in terms of the frequency of occurrence and time used for such interactions. The frequency of occurrence denotes the number of episodes observed for a specific category of interaction within a therapeutic session; the time used documents the time used for the episodes of a given category of therapeutic interaction.

Social, including therapeutic interaction, is no longer a domain of human–human interaction only, but has recently been introduced to the technology of socially interactive humanoid robots (HRs). Such HRs have a human-like appearance and frequently the capability to move body parts and might be equipped with technical "vision" or "hearing" and, most notably, with a capacity for social interaction. Among the user cases that have been investigated so far are HR companions providing interactions, supporting everyday life, or facilitating cognitive or physical training for the elderly (Andtfolk et al., 2022) or individualised social interactions for long-term care facility residents with dementia (Chen et al., 2020). In addition, HRs were used to improve social skills for children with autism spectrum disorders (Mengoni et al., 2017) or as coaches for physical exercises to promote arm function in children with cerebral palsy (Martin et al., 2020) or stretching exercises for low back pain relief (Blanchard et al., 2022). Furthermore, HRs have been designed and used to assist post-stroke patients in performing exercises during their rehabilitation process, at times for over extended periods of time (Koren et al., 2022), or with applications that were designed to provide human-like comprehensive guidance and interactions during therapeutic sessions (Forbrig et al., 2022). For such training-based therapy, therapeutic interactions, now provided by an HR, is a critical element.

This research was set forth to assess whether therapeutic interactions by an HR could comprehensively and reliably be assessed with the instrument THER-I-ACT that had been developed and validated for the situation when a human therapist interacts with patients therapeutically. In addition, this research intended to extend the scope of the assessment of therapeutic interactions using THER-I-ACT for situations where not only a therapist and a patient are present but also when an HR is the primary therapeutic coach, with the supervising staff (human being) being present at the same time or with the presence of an additional human "helper" who provides physical assistance as needed. The extended research question here was whether therapeutic interactions by either the humanoid robot, supervising staff, or helper when simultaneously present could comprehensively and reliably be assessed using the instrument THER-I-ACT.

2 Methods

2.1 Participants

The participants for this study could be stroke survivors who participated in the clinical trial E-BRAiN (Evidence-based Robot

Assistant in Neurorehabilitation; https://clinicaltrials.gov/ct2/show/NCT05152433) and completed the 2-week course of the humanoid robot-led therapy at one of the two study centres, i.e., the Universitätsmedizin Greifswald or the BDH-Klinik Greifswald. The eligibility criteria for the E-BRAiN trial were as follows: age ≥18 years, history of stroke (ischaemic stroke, non-traumatic intracerebral haemorrhage, and subarachnoidal haemorrhage), either stroke-related upper extremity paresis or visual neglect, not pregnant or breastfeeding, not living in custody, and providing informed consent.

The research was approved by the institution's review board (Ethikkommission der Universitätsmedizin Greifswald; date of approval: 10.05.2021).

2.2 Therapy

Stroke survivors included in this research [n = 17] participated in the clinical trial E-BRAiN and completed the 2-week course of humanoid robot-led therapy. They received ten arm rehabilitation sessions (one introductory session with a human therapist and nine sessions with the humanoid robot) as either the arm basis training (ABT) for moderate-to-severe arm paresis [n = 9] or arm ability training (AAT) for mild arm paresis [n = 8] using the digital therapy system E-BRAiN with a humanoid robot as the therapeutic agent.

Stroke survivors with a residual arm and hand paresis who could move their arm well against gravity (shoulder abduction and elbow flexion strength ≥4 out of 5 strength grades) have no more than moderate paresis of their fingers (index and thumb strength ≥3 out of 5 strength grades), preserved selective movements of their fingers, and were capable of grasping small objects qualified for the category "mild arm paresis", and hence, in AAT, those with more severe arm paresis (not fulfilling ≥1 criterion for mild arm paresis) fell into the category "moderate-to-severe arm paresis" and received ABT.

The AAT trains the sensorimotor efficiency by repetitive training. Eight tasks address different sensorimotor abilities such as aiming, steadiness, speed of finger movements, and finger and gross manual dexterity. During each therapeutic session, each of the eight tasks is repetitively practiced at the performance limit over four runs, each lasting approximately 1 min, while feedback as a summary of the knowledge of the results is provided intermittently. The trainee aims at improving her/his sensorimotor performance constantly. The ABT trains the selective movement capacity for individual joints of the arm and hand by repetitive movement attempts across the full range of passive movements in various directions for the shoulder, elbow, forearm, wrist, and fingers, addressed individually in a sequential way and physically assisted as needed. The graded exercises start with a single degree of freedom of the movements for all segments of the affected limb; each movement (selective active movement across the full range of a passive movement) is performed repetitively each day with assistance (e.g., weight support and completion of a movement) by a healthy subject (in the conventional setting a trained therapist) as needed (Platz, 2004; Platz et al., 2009).

During the first introductory session, the participants learnt how to perform the standardised training (AAT or ABT), while the human therapist in addition noted and decided on the individualisations indicated that were then used as prescriptions for the digital therapy system E-BRAiN.

FIGURE 1
Training setup. **(A)** AAT for stroke patients with mild arm paresis, a scenario with the patient, humanoid robot, and supervising staff. **(B)** ABT for patients with moderate-to-severe arm paresis, a scenario with the patient, humanoid robot, helper, and supervising staff. During nine consecutive sessions over 2 weeks, the therapeutic training (both AAT and ABT) was led by the humanoid robot providing therapeutic interactions as implemented in the digital system E-BRAiN with both training standards, e.g., audio-visual instructions and feedback and individualisation algorithms, e.g., for the feedback content. For safety reasons and to step in if needed, the sessions were accompanied by the supervising staff (sitting in the background). The participants with moderate-to-severe arm paresis receiving the arm basis training cannot necessarily perform the training movements completely by themselves. Since the robot cannot provide physical assistance and serves as a social agent (therapeutic interaction), these participants need a person ("helper") to provide physical assistance as needed for individual movements.

During the nine consecutive sessions, the therapeutic training was led by the humanoid robot ("robot") providing therapeutic interaction as implemented in the digital system based on both training standards and individualisation algorithms. For safety reasons and to step in if needed, all humanoid robot-led sessions were accompanied by a supervising staff ("therapist"). The participants with moderate-to-severe arm paresis receiving the arm basis training could not necessarily perform all training movements by themselves and could perform them only to a variable degree, e.g., only with a limb weight support or over a limited range. Since the robot could not provide physical assistance and served as a social agent only (therapeutic interaction), these participants received physical assistance as needed provided by a "helper." The helper was not a trained therapist, but was also using the instructions provided by the robot. In this research, the helper was a non-therapeutic staff member (e.g., a person with administrative or scientific duties).

2.3 Video recording of sessions and THER-I-ACT ratings

The robot-led training sessions had audio-visually been video recorded twice, both on the first and the last (9th) session. Hence, for each participant, data of the two sessions were available for offline rating of the therapeutic interactions. The videorecorder was placed to cover the therapy scenario, its agents, the interface used for visual displays (tablet or monitor), and to show the training activity currently performed. Since the therapeutic interaction implemented in the system is either verbal or audio-visual accompanied by verbal phrases, the audio-recording was also mandatory and used for the analysis of therapeutic interactions.

The scenarios, as video recorded, differed for the following two types of trainings (compare Figure 1):

A. AAT: for stroke patients with mild arm paresis, the scenario with a patient, humanoid robot, and supervising staff (three interactive agents).
B. ABT: for patients with moderate-to-severe arm paresis, the scenario with a patient, humanoid robot, helper, and supervising staff (four interactive agents).

Even though the robot is programmed to provide all therapeutic interactions necessary, there might be situations where the therapist or the helper steps in naturally and spontaneously (they are not given instructions to do so) and provides additional therapeutic interactions.

Therefore, any therapeutic interaction as performed either by a robot, therapist, or helper was documented.

The two trained raters (Ann Louise Pedersen and Philipp Deutsch) independently analysed and documented the therapeutic interactions observed in the two video-recorded sessions per participant using the instrument THER-I-ACT and its manual. THER-I-ACT measures both the occurrence/frequency and the timing of the therapeutic interactions in the thematic fields of "information provision," "feedback," and "bonding" with a variety of pre-defined categories in each thematic field and in addition provides a global rating of the focussed attention and engagement for both the patient and therapist (for details, see Platz et al., 2021).

2.4 Sample size determination

For clinical purposes, at least a moderate inter-rater reliability as indicated by an intraclass correlation coefficient (ICC) of 0.60 or higher was warranted. For testing H_0:ICC = 0.20 (lack of reliability) *vs.* H1:ICC = 0.60 (moderate reliability) with the two independent raters and alpha = 0.05 and beta = 0.20, a sample of 27 observations would be necessary (Shoukri et al., 2004). A sample of that magnitude was planned to be recruited so that the documented ICCs of 0.6 or higher could be regarded as substantiated. Since the helper was only present and, hence, could only be observed in ABT sessions, a total of 34 observations (17 participants, AAT and ABT sessions) were included, allowing for 18 observations (ABT sessions) with a helper present.

Accordingly, the data of the first 17 participants of the E-BRAiN clinical trial were planned to be used for this study.

2.5 Statistical analyses

The baseline characteristics of the study population are presented using descriptive statistics (count, mean, and standard deviation).

For all THER-I-ACT measures, i.e., the frequencies and time used for the individual categories of interaction and the singular rating of the presence and engagement by the therapist (separately assessed for the robot, therapist, and helper, respectively) and of the focussed attention and engagement by the patient, the following statistics were calculated: the mean for each rater (rater 1 (R1) and rater 2 (R2)) and ICC.

The ICC is the appropriate statistic to assess the consistency of the ratings for intervals and ratio levels of the measurement (Gisev et al., 2013). In the presented research, two-way random-effects models have been used for ICC estimation, since each item was assessed by both raters. Specifically, the ICC (1, 2) according to Shrout and Fleiss (1979) had been calculated using a SAS macro written by Robert M. Hamer, Ph.D., Virginia Commonwealth University, 2-7-1991.

3 Results

3.1 Participants

The baseline characteristics of the participants are presented in Table 1.

The sample of stroke survivors recruited from as early as a few weeks to some years after a stroke included female and male participants after either right or left brain damages of the ischaemic or hemorrhagic nature with a wide age distribution and minimal to considerable disability (Barthel Index), minimal to moderate emotional distress, and a considerable range of arm motor dysfunctions (mild to severe). Hence, the sample, even though small, covered a considerable spectrum of clinical presentations that could be met after a stroke supporting a broader applicability of the study results.

3.2 Observed therapeutic interactions during therapy with a humanoid robot

Table 2 presents all THER-I-ACT observations made by both the independent assessors, rater 1 (R1) and rater 2 (R2), respectively. The observations from 17 participants and two sessions for each participant are presented as a group mean for all individual categories specified by THER-I-ACT and both their frequency of occurrence during a therapeutic session (count) and the time used for that type of interaction (in seconds).

Since THER-I-ACT (Platz et al., 2021) comprehensively defines categories of therapeutic interactions, in many therapeutic situations only a subset of the possible types of therapeutic interactions can be expected.

TABLE 1 Study population characteristics (n = 17).

	Mean/sd n (%)	Min–max n (%)	n
Age (mean/sd; min–max)	62.4/14.3	36–81	
Sex (female; male) (n (%))	11 (65%)	6 (35%)	
Stroke type (ischaemic; ICH) (n (%))	14 (82%)	3 (18%)	
Affected brain (left; right) (n (%))	6 (35%)	11 (65%)	
Time post-stroke (weeks) (mean/sd; min–max)	86/115	3–367	
NIHSS (0–42) (mean/sd; min–max)	4.6/2.1	1–9	
Barthel index (0–100) (mean/sd; min–max)	79/18	35–100	
HADS (0–42) (mean/sd; min–max)	12.3/5.9	6–25	16[a]
FM arm[a] (0–66) (mean/sd; min–max; n)	20.6/6.7	12–30	9
BBT[b] (blocks/minute) (mean/sd; min–max; n)	32.5/11.6	18–44	8
NHPT[b] (sec) (mean/sd; min–max; n)	94.9/133.2	33.0–396	7[b]
Type of training therapy (ABT[a]; AAT[b])	8	9	

AAT, arm ability training; ABT, arm basis training; BBT, Box and Block Test; FM arm, Fugl–Meyer arm motor score; HADS, Hospital Anxiety and Depression Scale; ICH, intracerebral haemorrhage; NHPT, Nine Hole Peg Test; NIHSS, National Institute of Health Stroke Scale; NT, neglect therapy; min, minimum; max, maximum; sd, standard deviation; superscript letters (AAT[a] and ABT[b]) indicate the different types of therapies and how they relate to both the treated syndromes and the tests used for the baseline assessment, respectively.

[a]One participant did not want to disclose their personal emotional information.

[b]One participant receiving AAT could not perform the NHPT during the baseline assessment.

Table 2 indicates the types, frequency, and time used for therapeutic interactions that could be observed in robot-led therapy sessions, both as provided by the humanoid robot itself ("robot interaction") or by the supervising staff ("therapist") or a "helper" (ABT only) spontaneously stepping in and providing the additional therapeutic interaction. As such, the table presents the general structure of the data used for inter-rater reliability analyses, descriptively, and can be verbally summarised as follows:

The observations made indicate that the humanoid robot has by far been the dominating agent providing therapeutic interactions. Its therapeutic interaction is characterised by a few longer information provision events that relate to the individual treatment goal or the applied training (i.e., AAT or ABT) in more general terms ("training specifications") and by many short instructions given. The feedback has been given by the robot as knowledge of the results, mostly neutral ("knowledge of result"), at times associated with positive social stimuli. The work alliance supporting therapeutic interactions by the robot was not infrequently observed and fell in the category of "showing interest in person treated."

Therapeutic interactions by the supervising staff occurred infrequently and, if so, mainly as short instructions and once or twice during a session as "showing interest in person treated."

While again much less frequent than the robot's therapeutic interaction, the helper spontaneously provided additional instructions and on average several times the interaction of "showing interest in person treated", with both types of interactions, more frequently than the supervising staff.

The patients, supervising staff, and helper received high scores for the global rating of their focussed attention and engagement as perceived by the rater, while the robot received only intermediate scores.

3.3 Inter-rater reliability

The inter-rater reliability statistics (ICC) for individual THER-I-ACT categories as based on 34 sessions (17 participants' first and last session with the robot and a subset of 18 sessions with a helper being present (ABT only)) are presented in Table 3.

For all categories of therapeutic interaction by the humanoid robot, the ICC was ≥0.90 for both the frequency of occurrence and time used for the type of interaction indicating a high degree of reliability.

Even though rather infrequently observed, therapeutic interactions by the supervising staff ("therapist") could mostly be documented reliably (ICC ≥0.90) with two exceptions, i.e., introducing own personal aspects and (any) "other type of interaction"; both of them occurred only exceptionally.

The therapeutic interaction by a helper (ABT sessions only), while somewhat more frequently observed than the interaction by the supervising staff, yet much less than the interaction by the robot, could nevertheless be reliably documented (ICC ≥0.85).

The ICC was similarly high for an overall subjective rating of the concentration and engagement of patients (ICC 0.87), somewhat less, but still substantial for the helper (ICC 0.77), but not for the rating "presence and engagement" of the supervising staff sitting in the background (ICC 0.00).

4 Discussion

With the number of people living with the aftermath of stroke being on the rise globally (Nguyen et al., 2019) and the intensive individualised rehabilitative training having the potential to reduce

TABLE 2 THER-I-ACT observations: The observations (mean) for individual categories by a rater (17 participants; two sessions each).

Themes and individual aspects	Mean for robot interaction				Mean for therapist				Mean for helper interaction			
	Frequency		Time used		Frequency		Time used		Frequency		Time used	
Number of sessions evaluated	34		34		34		34		18		18	
	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2	R1	R2
1. Provision of information												
a. Treatment goal	2.8	2.8	130	128	<0.1	<0.1	<1	<1	0	0	0	0
b. Training specifications	0.6	0.6	79	79	0	0	0	0	0.1	0	<1	0
c. Instructions	287.5	287.2	1519	1529	8.2	7.9	34	36	29.9	30.0	57	58
2. Feedback												
a. Knowledge of performance (KP) (unless corrective)	0	0	0	0	0.2	0.1	<1	<1	2.2	1.8	2	2
b. KP with positive social stimuli	0	0	0	0	0.1	0.1	<1	<1	0.6	0.7	<1	1
c. KP with negative social stimuli	0	0	0	0	0	0	0	0	0	0	0	0
d. Corrective KP (cKP)	0	0	0	0	0	0	0	0	0	0	0	0
e. cKP with positive social stimuli	0	0	0	0	0	0	0	0	0	0	0	0
f. cKP with negative social stimuli	0	0	0	0	0	0	0	0	0	0	0	0
g. Knowledge of result (KR)	16.6	16.5	147	163	0.2	0.3	<1	<1	0	0	0	0
h. KR with positive social stimuli	2.2	2.2	17	17	0.2	0.2	<1	<1	0	0	0	0
i. KR with negative social stimuli	0	0	0	0	0	0	0	0	0	0	0	0
3. Motivational interactions												
a. Other than KP or KR	1.2	1.2	10	10	0.3	0.2	<1	1	0.3	0.3	<1	<1
4. Bond												
a. Showing interest in the person treated	31.4	31.6	201	207	1.7	1.9	14	13	8.6	8.8	18	17
b. Personal aspects (treating person)	0	0	0	0	0	<0.1	0	<1	0.1	0.1	<1	<1
c. Responsivity	0	0	0	0	1.4	1.6	4	4	0.5	0.5	1	1
d. Conflict solving	0	0	0	0	<0.1	<0.1	1	1	0.1	0.1	<1	<1
5. Other types of interaction	0	0	0	0	0.3	0.2	<1	<1	0.3	0.4	1	1
6. Presence (concentration) and engagement (treating person) (0–10)	5.0	5.0			9.0	9.5			10	9.5		
7. Focussed attention and engagement (patient) (0–10)	8.6	8.6			n.a.	n.a.			n.a	n.a.		
Length of the therapeutic session (minutes)	81	81										

R1 and R2, rater 1 and 2, respectively; frequency, frequency of the occurrence of a therapeutic interaction within a session (count) and the mean across observations rounded to one decimal; time used, time used for therapeutic interactions within a session (in seconds) and the mean across observations rounded to seconds (without decimals); KP, knowledge of performance; KR, knowledge of result; [1]presence (concentration) and engagement by the supervising therapist observable and rated only for 28 sessions.

stroke-related disabilities (Joy and Carmichael, 2021), one way that had been entertained to support prolonged rehabilitation is the use of digital therapeutic systems based on the HR technology.

The acceptance and use of the HR technology will likely be influenced by the enjoyment and ease of use experienced by its users and their trust in the HR application (Jung et al., 2021). The factors related to the robot itself, specifically, its functional performance, seem to have the greatest impact on trust (Hancock et al., 2011; Koren et al., 2022). Such functional performance is related to the specificity of the training provided by an HR application, its potential to adapt to the individual necessities, and any training progress, as well as its therapeutic interaction.

Indeed, research on the use of HRs for training-based rehabilitation has acknowledged the relevance of and implemented therapeutic interactions as verbal and non-verbal (e.g., demonstration) instructions and performance-based feedback (Martin et al., 2020; Blanchard et al., 2022; Koren et al., 2022).

The research on human–robot interactions, thus far, has focussed on the users' perspective and assessed enjoyment, ease of use, and trust from the users' perspective (Jung et al., 2021). The functional performance of an HR, however, is defined on the robot's side with therapeutic interactions being an integral part of it. Given its prominent role, a standardised assessment of an HR's therapeutic interaction would be equally warranted.

In this research, the instrument THER-I-ACT that had been developed and validated for the situation when a human therapist interacts with patients therapeutically (Platz et al., 2021) has now been assessed when applied to document the therapeutic interaction performed by an HR. Here, it could be demonstrated that the

TABLE 3 THER-I-ACT observations: The inter-rater reliability for individual categories (rater r = 2, participants n = 17, and sessions per participants s = 2).

Themes and individual aspects	ICC for robot interaction		ICC for therapist		ICC for helper interaction	
	Frequency	Time used	Frequency	Time used	Frequency	Time used
Number of sessions evaluated	34	34	34	34	18	18
1. Provision of information						
a. Treatment goal	1.00	1.00	1.00	1.00	n.a	n.a
b. Training specifications	1.00	1.00	n.a	n.a	1.00	1.00
c. Instructions 1.00	1.00	1.00	1.00	0.99	1.00	0.98
2. Feedback						
a. Knowledge of performance (KP) (unless corrective)	n.a	n.a	0.96	0.96	0.99	0.96
b. KP with positive social stimuli	n.a	n.a	1.00	1.00	0.99	0.99
c. KP with negative social stimuli	n.a	n.a	n.a	n.a	n.a	n.a
d. Corrective KP (cKP)	n.a	n.a	n.a	n.a	n.a	n.a
e. cKP with positive social stimuli	n.a	n.a	n.a	n.a	n.a	n.a
f. cKP with negative social stimuli	n.a	n.a	n.a	n.a	n.a	n.a
g. Knowledge of result (KR)	1.00	0.90	0.96	0.90	n.a	n.a
h. KR with positive social stimuli	0.99	0.99	1.00	0.96	n.a	n.a
i. KR with negative social stimuli	n.a	n.a	n.a	n.a	n.a	n.a
3. Motivational interactions						
a. Other than KP or KR	1.00	1.00	0.92	0.96	1.00	0.85
4. Bond						
a. Showing interest in the person treated	1.00	0.99	0.98	1.00	0.99	0.98
b. Personal aspects (treating person)	n.a	n.a	0.00	0.00	1.00	0.88
c. Responsivity	n.a	n.a	0.99	1.00	1.00	0.90
d. Conflict solving	n.a	n.a	1.00	0.98	1.00	0.92
5. Other types of interaction	n.a	n.a	0.79	0.34	0.92	0.98
6. Presence (concentration) and engagement (treating person) (0–10)	n.a[a]		0.04[b]		0.77	
7. Focussed attention and engagement (patient) (0–10)	0.87					
Length of the therapeutic session (minutes)	1.00					

Aside from the number of sessions (= count), all the other statistics provided are ICCs, for the consistency of measurements between the two independent raters (rater data presented in Table 2).
ICC, intraclass correlation coefficient; frequency, frequency of occurrence of therapeutic interactions within a session (count); time used, time used for therapeutic interactions within a session (in seconds); KP, knowledge of performance; KR, knowledge of result; n.a., not applicable or the type of interaction not observed.
[a]Presence (concentration) and engagement by the robot invariably rated as "5".
[b]Presence (concentration) and engagement by the supervising therapist rated only for 28 sessions.

therapeutic interaction of an HR leading neurorehabilitation training sessions as a social agent providing information, giving instructions and feedback, and taking interest in a person during training could equally, comprehensively, and reliably be assessed with THER-I-ACT. The ICC was ≥0.90 for both the frequency of occurrence and time used for all types of the robot's therapeutic interactions. This indicates a very high degree of reliability for the documentation of these highly detailed categories of therapeutic interactions by two independent trained assessors.

In addition, this research extended the scope of the assessment of the therapeutic interaction using THER-I-ACT for situations where not only a therapist and a patient are present but also when a humanoid robot is the primary therapeutic coach, with the supervising staff being present at the same time and, at times, with the presence of a human "helper" who provides physical assistance as needed (ABT). It could be shown for these scenarios that not only the therapeutic interaction by the humanoid robot but also the additional (while much less frequent) spontaneously occurring therapeutic interaction both by the supervising staff and a helper could reliably be documented. The exceptions were the interactions that hardly ever occurred.

The limitations of the research that are noteworthy are the limited sample and the types of therapies assessed. While the sample of stroke survivors included showed a relevant variability of sociodemographic and clinical characteristics and while the two types of therapies (i.e., AAT and ABT) have different characteristics and associated therapeutic interactions, it remains a possibility that the high degree of the inter-rater reliability observed might not equally apply to all therapeutic situations (e.g., different patients groups, other types of therapies, and therapeutic interaction categories that were not observed in this research, e.g., the corrective knowledge of the performance). In addition, the high degree of the inter-rater reliability was documented when the raters had been well trained to use the instrument. It is, however, conceivable that reaching the competence to assess therapeutic interactions of an HR necessitates less training for a rater compared to that of the assessment of a human agent's therapeutic interaction. The algorithmic setup of an HR's interaction makes it more standardised (even when individualised) compared to the spontaneous human communication that can have a complex structure and a high degree of variability.

In conclusion, the research data presented support the notion that therapeutic interactions can reliably be assessed with the instrument THER-I-ACT, not only in the traditional patient–therapist setting, as shown previously (Platz et al., 2021), but also in a digital setting with a humanoid robot as the therapeutic agent. As such, it offers the possibility to perform a video-based assessment of an HR's therapeutic interaction as one aspect of its functional performance. Furthermore, THER-I-ACT can reliably be used to document the therapeutic interaction for scenarios where more than one therapeutic agents are present, e.g., when both a humanoid robot and human agents provide therapeutic interactions. As such, the data support the use of THER-I-ACT for these situations and extend the instrument's validated application context.

Data availability statement

The datasets presented in this article are not readily available because the data can only be used for the purpose and by the persons agreed to, with informed written consent by participants. Requests to access the datasets should be directed to thomas.platz@uni-greifswald.de.

Ethics statement

The studies involving human participants were reviewed and approved by Ethikkommission der Universitätsmedizin Greifswald. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

TP designed and wrote the manuscript. All authors critically reviewed the manuscript for intellectual content and approved its final version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Analysis of the therapeutic interaction provided by a humanoid robot serving stroke survivors as a therapeutic assistant for arm rehabilitation

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Objective: To characterize a socially active humanoid robot's therapeutic interaction as a therapeutic assistant when providing arm rehabilitation (i.e., arm basis training (ABT) for moderate-to-severe arm paresis or arm ability training (AAT) for mild arm paresis) to stroke survivors when using the digital therapeutic system Evidence-Based Robot-Assistant in Neurorehabilitation (E-BRAiN) and to compare it to human therapists' interaction.

Methods: Participants and therapy: Seventeen stroke survivors receiving arm rehabilitation (i.e., ABT [n = 9] or AAT [n = 8]) using E-BRAiN over a course of nine sessions and twenty-one other stroke survivors receiving arm rehabilitation sessions (i.e., ABT [n = 6] or AAT [n = 15]) in a conventional 1:1 therapist–patient setting. Analysis of therapeutic interaction: Therapy sessions were videotaped, and all therapeutic interactions (information provision, feedback, and bond-related interaction) were documented offline both in terms of their frequency of occurrence and time used for the respective type of interaction using the instrument THER-I-ACT. Statistical analyses: The therapeutic interaction of the humanoid robot, supervising staff/therapists, and helpers on day 1 is reported as mean across subjects for each type of therapy (i.e., ABT and AAT) as descriptive statistics. Effects of time (day 1 vs. day 9) on the humanoid robot interaction were analyzed by repeated-measures analysis of variance (rmANOVA) together with the between-subject factor type of therapy (ABT vs. AAT). The between-subject effect of the agent (humanoid robot vs. human therapist; day 1) was analyzed together with the factor therapy (ABT vs. AAT) by ANOVA.

Main results and interpretation: The overall pattern of the therapeutic interaction by the humanoid robot was comprehensive and varied considerably with the type of therapy (as clinically indicated and intended), largely comparable to human therapists' interaction, and adapted according to needs for interaction over time. Even substantially long robot-assisted therapy sessions seemed acceptable to stroke survivors and promoted engaged patients' training behavior.

Conclusion: Humanoid robot interaction as implemented in the digital system E-BRAiN matches the human therapeutic interaction and its modification across therapies well and promotes engaged training behavior by patients. These characteristics support its clinical use as a therapeutic assistant and, hence, its application to support specific and intensive restorative training for stroke survivors.

KEYWORDS

robot, training, arm, stroke, interaction, social, artificial intelligence

1 Introduction

Stroke is the second leading cause of death and a very frequent cause of acquired disability globally with the number of people living with the aftermaths of stroke increasing considerably over the last three decades (GBD, 2016 Stroke Collaborators, 2019).

Neurorehabilitation, the type of medical service providing therapy to promote functional recovery, can reduce stroke-related disability leading to a higher number of people that regain the capacity to care for themselves and, hence, to continue to live on their own (Stroke Units Trialist Collaboration, 2013; Langhorne et al., 2020).

This success is related to the brain's capacity to recover functionally by reorganizing brain network sub-serving functions (Koch et al., 2021). Recovery of brain function occurs both spontaneously and can be enhanced by specific intensive training of the functions to be restored, that is, by "neural repair therapy" (Joy and Carmichael, 2021).

Indeed, training that addresses impairments (impaired body functions) specifically and with high enough intensity using standardized repetitive training protocols for the targeted functions (Platz, 2004) proved to be superior to conventional therapy even when the same therapeutic time was allocated (Platz et al., 2009). Even though such evidence-based therapy is recommended by international organizations (Platz et al., 2021a), there is a lack of implementation of rehabilitation therapy due to a shortage of skilled staff. This is partially true for high-income countries (HICs), but even more pressing in low- and middle-income countries (LMICs) (Owolabi et al., 2021). As a consequence, there is a need for more specific and intensive "neural repair therapy" that cannot be addressed by the services and human resources available. Also, in future, the demand might further increase secondary to demographic changes (GBD, 2016 Stroke Collaborators, 2019).

Potential solutions for the problem might be an integration of patient-led training or family-led training into the individual rehabilitation process. Unfortunately, the special knowledge necessary to promote functional recovery, the required individual adaptation of specific training schedules, and the necessary motivational requirements for extended periods of training all seem to limit the potential to effectively exploit both patient-led training and family-led training for the rehabilitation of people with neuro-disabilities, for example, after stroke (Tyson et al., 2015; Lindley et al., 2017). High enough training adherence to promote recovery could even not be achieved when patient-led training was assessed as feasible and acceptable by stroke survivors themselves (Horne et al., 2015).

In that situation, and when human resources to provide therapy presumably cannot be expanded to the extent needed to combat stroke-related disability effectively, digital and/or robotic therapeutic systems might be one solution to fill the gap.

The support therapists provide during training-based therapy is complex, that is, providing information including instructions, feedback, and motivating comments, as well as physical guidance and help if necessary. Principally speaking, digital and/or robotic therapeutic systems might serve any of these purposes or even all of them. Their perceived usefulness, for example, the degree to which a person believes that using a particular system would enhance her or his rehabilitation, would rest on any system's capabilities (Davis, 1989).

Indeed, over the last few decades, mechanical rehabilitation robots, end-effector-based or exoskeleton-type, have been developed that support repetitive training of selective movements for stroke survivors with severe paresis with a need for physical assistance during their exercises (Mehrholz et al., 2018). Such robots offer a high degree of repetitive practice, can track human performance during task execution, and are supported by a substantial body of evidence to be beneficial for restoration of motor function. For each robot, they are, however, limited to only few degrees of freedom (e.g., shoulder and elbow movements only) that they assist to train. Accordingly, their application—while recommended for additional practice (Platz et al., 2021b)—is limited to just few aspects of training and a small subgroup of stroke survivors (for each type of robot). Furthermore, as these systems do not comprehensively guide through therapeutic sessions, there is still the need for close therapeutic supervision during their use in neurorehabilitation and, hence, human resources.

Humanoid robots on the other side have the potential advantage that they can be used as socially interactive robots. Their humanoid appearance might help to build trust in their guidance when their general functionality is well adapted to the service offered by them (Hancock et al., 2011; Jung et al., 2021).

While use cases had been published where socially interactive humanoid robots were designed to provide physical assistance, again the technological affordances for physical help (including safety issues) are complex and, therefore, thus far limit such technology to a small set of tasks to be supported by them. Examples are a robot named RIBA (Robot for Interactive Body Assistance) with human-type arms that is designed to perform heavy physical tasks requiring human contact such as transferring a human from a bed to a wheelchair and back (Mukai et al., 2010), a robotic system for the specific dressing scenario "putting on a shoe" (Jevtić et al., 2019), or a physically interactive humanoid robot application for a human range-of-motion training at the shoulder with skeleton recognition-based motion generation (Miyake et al., 2022).

A further option would be to design a socially active humanoid robot that does not provide physical assistance but acts as a therapeutic assistant without physical contact, hence more like a coach.

A strength of such a dedicated system would be that it could be conceptualized to comprehensively guide through therapeutic sessions, considerably reducing the need for close therapeutic supervision during their use in neurorehabilitation. Also, such a humanoid robot-based digital therapeutic system could be designed, developed, and consequently used as a platform for a wide variety of types of neurorehabilitation training therapy. For that purpose, such systems should both have artificial intelligence (AI) embedded that guarantees the individualized application of the professional knowledge necessary during training sessions and sufficiently support motivational factors to ensure prolonged engaged training even among people with brain damage.

Technology that provides one aspect only (e.g., digital health applications with training schedules) may fall short of the needs of people with neuro-disabilities being candidates for restorative training.

Socially interactive robots might provide a technology base to address the interpersonal aspects of training more sufficiently. Indeed, as human beings, we are inclined to accept a humanoid robot as a kind of social partner (Darling et al., 2015). Also, interviews with stroke survivors who underwent a long-term rehabilitation process, assisted by either a socially interactive humanoid robot or a computer interface, support the notion that socially interactive humanoid robots augment rehabilitative therapies beyond a standard computer (Koren et al., 2022).

The digital therapy system Evidence-Based Robot-Assistant in Neurorehabilitation (E-BRAiN) (https://www.ebrain-science.de/en/home/) that was used in this research project allows a humanoid robot to lead stroke survivors receiving rehabilitation treatment through therapeutic sessions, to give instructions for carefully selected training exercises, provide feedback, and support their motivation. In this context, the robot's task is not to take therapeutic decisions, but to autonomously continue a repetitive training schedule once it has been decided on, which was individually adapted and introduced to a stroke survivor by a human therapist (Forbrig et al., 2022).

The digital therapy system E-BRAiN was specifically designed to be used as a socially interactive humanoid robot as technology, to establish AI that provides (A) professional therapeutic training knowledge for both arm rehabilitation and neglect therapy based on types of therapy with evidence to support their effectiveness for recovery post stroke, (B) to lead through (daily) therapy sessions in an autonomous way with all communication and therapeutic interaction necessary, and (C) to individualize all activities based on individual data (e.g., clinical characteristics, results of assessment, therapeutic goal, and progress made during training).

The system further supports referring expressions in a real-time text-generation system so that generated texts can be adapted to the user in the best possible way (Felske et al., 2022).

In consequence, the therapeutic interaction is complex including provision of information (related to individual rehabilitation goals, training specifications, and training instructions), feedback (in the form of knowledge of result or performance, with or without additional social stimuli), and bond-related interactions (showing interest in the person treated).

Equipped in this way, the digital therapy system E-BRAiN is now used to treat stroke survivors.

The aim of this research was to characterize the humanoid robot's therapeutic interaction when providing arm rehabilitation (i.e., arm basis training (ABT) for moderate-to-severe arm paresis or arm ability training (AAT) for mild arm paresis) to a group of stroke survivors and its change over time (from the first to the last session with the robot) when using the digital therapeutic system E-BRAiN and to compare the humanoid robot's therapeutic interaction to human therapists' interaction.

The sample of stroke survivors using the system E-BRAiN for arm rehabilitation are participants of a clinical trial to test the system's acceptability, safety, and clinical benefit (University Medicine Greifswald, 2021). Observations made with the control sample of stroke survivors result from the provision of the same therapies in the same context, but in the conventional 1:1 human therapist–patient setting.

2 Methods

2.1 Technical characterization of the E-BRAiN system

2.1.1 Technical setup (hardware)

The robot system consists of multiple devices with a central architecture, as presented in Figure 1.

In this figure, the technical setup and roles of the patients, therapists, and technical team (programmers) are depicted (Forbrig et al., 2021). All devices are connected *via* Wi-Fi in the same network. The main program files of the system are hosted on a central computer running on Cent OS (Linux operating system; https://www.linux.org). The software of the therapy application consisting of python dialog scripts, database, therapy management interface, and communication is deployed on this computer. During a therapy session, all device interactions are transmitted *via* the OASIS standard messaging protocol for the Internet of Things (IoT) MQTT (https://mqtt.org/) and processed on the computer. The main focus is to offer therapy sessions for the patient. To organize a therapy and its sessions, a therapist creates a patient entry in the system database *via* the therapy administration interface and configures the therapy sessions. The interface can be accessed on any generic computer inside the system network. The humanoid robot Pepper (https://www.unitedrobotics.group/products-services/hardware/), the Android OS tablet, and the touch monitor are running apps developed for the therapies. The robot provides the verbal dialog to patients while the other devices are used in parallel to display images, videos, and subtitles (e.g., for instruction purposes), diagrams (e.g., for knowledge of result feedback), or plain text (e.g., "do you need a break?") and to support the robot program with patients' entries (e.g., "ready to continue"). The touch monitor with a 27-inch screen is used for the neuro-visual therapy of the project (not used in this study population). A system programmer of the technical team has access to the system to check for errors and possibly fix errors on the application.

2.1.2 Robot control algorithm

For a flexible and precise determination, of what content and robot feedback is provided at a certain point of a therapy, the therapy

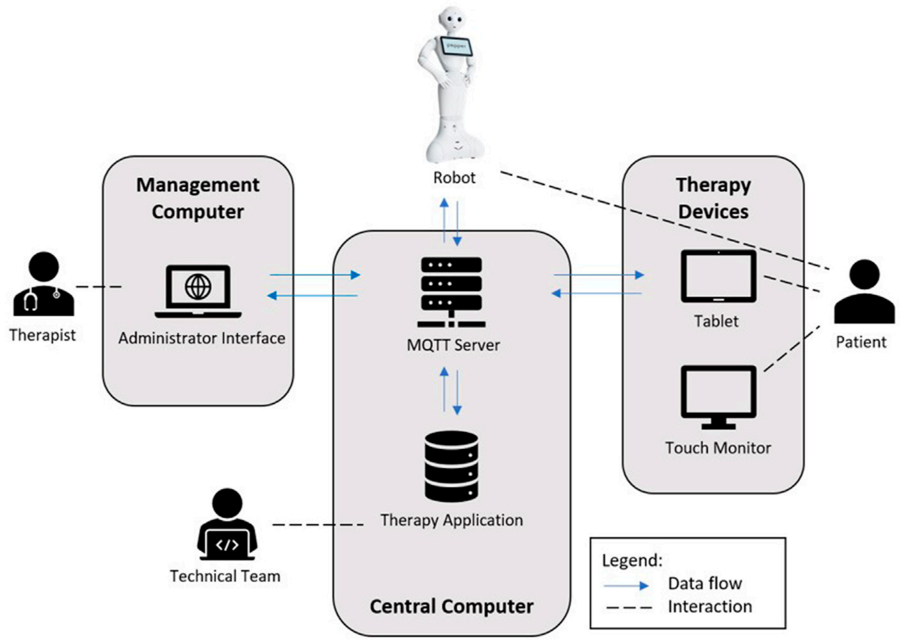

FIGURE 1
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interaction is designed around the concept of a "finite-state machine" (Bundea et al., 2021). The robot operates in these therapy "states," a small part of the therapy program script. The robot starts at the "start" therapy state and proceeds to the next state either after a pre-defined time or a patient confirmation until the final state "saying goodbye" has been reached.

Therapy states are linked with media content and robot actions to be executed at the point of time, when a state is called. When the therapy dialog script transits to another therapy state, a message will be sent to all connected devices, which involves the robot and either the tablet or monitor. The devices will then interpret the message and execute possible commands such as displaying videos or providing speech feedback.

This design of therapy states allows for a flexible robot control, whereby being able to pause at any given therapy state and (re-)entering any other therapy state are the most important features. This control pattern and therapy design also helped to ensure a patient sees exactly the pre-defined contents in the correct order.

2.1.3 Content of social interaction

Stroke survivors need intensive specific training schedules, frequently for a prolonged period. For the realization of such training schedules, patients frequently have to be provided with close supervision and professional guidance based on therapeutic interaction guaranteeing information provision and specific individualized feedback as well as work alliance and motivation supporting personal contact.

With the E-BRAiN system, the humanoid robot's social interaction is set up to fulfill all of these requirements with standards for each type of training implemented (e.g., the AAT and the ABT) and dialog structures for complete training sessions starting with a personalized "welcome" to closing the therapeutic session.

Specifically, the humanoid robot welcomes the patient individually, explains (A) the therapeutic goal, (B) the prescribed therapy and how it works, and (C) individual training tasks, (D) provides instructions audiovisually (using photos and videos), (E) gives feedback according to the type of therapy and any progress, and (F) asks and provides breaks as needed.

The therapeutic interaction is individualized, based on knowledge about the patient from the medical chart, assessments made before training, and therapeutic progress during training sessions.

2.2 Participants

Participants for this study could be stroke survivors who participated in the clinical trial E-BRAiN (https://clinicaltrials.

FIGURE 2
The therapeutic scenarios for the digital therapeutic system E-BRAiN using a humanoid robot to provide therapeutic interaction during arm rehabilitation sessions [i.e., AAT for mild arm paresis **(A)** and ABT for moderate-to-severe arm paresis **(B)**] for stroke survivors. It should be noted in the scenario for the AAT (A), the patient is able to train the (mildly) affected right arm self-sufficiently; here, the robot provides all therapeutic interactions (information provision, feedback, and bond-related interaction) while the patient is led through a sequence of training tasks; the supervising staff in the background is only monitoring the situation and ready to step in in case the system designed to run autonomously showed an error or a patient's need could not be met by the system. The situation for the ABT is similar with regard to the role of the humanoid robot and supervising staff; here, however, a helper is integrated as a third active agent (in addition to the patient and humanoid robot), a person not qualified as a therapist, who is also guided by the humanoid robot and provides physical assistance as needed for the training of a severely paretic arm.

gov/ct2/show/NCT05152433) and completed the 2-week course of humanoid robot-led therapy. Eligibility criteria for the E-BRAiN trial are as follows: age ≥ 18 years, history of stroke (ischemic stroke, non-traumatic intracerebral hemorrhage, and subarachnoidal hemorrhage), either stroke-related upper extremity paresis or visual neglect, not pregnant or breastfeeding, not living in custody, and providing informed consent.

Data of the first 17 participants of the trial receiving arm rehabilitation as either ABT for moderate-to-severe arm paresis or AAT for mild arm paresis were planned to be used for this study.

The sample of control subjects receiving therapy in the conventional 1:1 human therapist–patient setting was a convenience sample of 21 participants of age ≥ 18 years, with a history of stroke (ischemic stroke, non-traumatic intracerebral hemorrhage, and subarachnoidal hemorrhage), and stroke-related incomplete upper extremity paresis interested in a 1-week course of complimentary intensive daily arm rehabilitation (ABT or AAT), and providing informed consent.

The research was approved by the institution review board (Ethikkommission der Universitätsmedizin Greifswald; date of approval: 10.05.2021).

2.3 Participant characteristics

For all participants, the following characteristics were documented at study entry: age, gender, types of stroke etiology (i.e., ischemic stroke, non-traumatic intracerebral hemorrhage, or subarachnoidal hemorrhage), time post-stroke (in weeks), and degree of neuro-impairment (National Institute of Health Stroke Scale (NIHSS)) (Brott et al., 1989) and neuro-disability (Barthel Index) (Mahoney and Barthel, 1965), as well as emotional distress (Hospital Anxiety and Depression Scale (HADS)) (Snaith, 2003), in addition to arm motor function (i.e., Box and Block Test (BBT) for participants with mild arm paresis or Fugl–Meyer Arm Motor score (FM Arm) for participants with moderate-to-severe arm paresis) (Fugl-Meyer et al., 1975; Platz et al., 2005).

2.4 Therapies applied

The AAT is based on eight training tasks addressing different sensorimotor abilities such as aiming, steadiness, speed of finger movements, and finger and gross manual dexterity. With the AAT, stroke survivors train their sensorimotor efficiency by repetitively executing each task at their individual performance limit in (four) blocks (each) lasting approximately 1 minute and constantly trying to improve their speed of execution while keeping the required level of precision. During the AAT, both the human therapist and humanoid robot provide information including instructions and feedback. The feedback is given as intermittent summary knowledge of result (KR) both with the time needed for each block of execution (per task) showing within-session progress for each task separately and the average time across (four) blocks for each day and task compared to the corresponding measure from the previous days of training indicating the learning process across days.

The ABT trains selective movement capacity for individual joints of the shoulder, elbow, forearm, wrist, and fingers by repetitive movement attempts across the full range of passive movements in the various directions possible in these joints. Each day, all movements are addressed individually and repetitively in a consecutive sequential way. Since patients receiving the ABT have moderate-to-severe arm paresis and cannot perform these movements, or only to a limited extent, or only without weight-bearing affordances, they are physically assisted as needed during the training (Platz, 2004; Platz et al., 2009). Each movement (depending on an individual's capacity) may be performed without the need for weight bearing of the limb (weight bearing is taken over by a therapist) or alternatively against gravity or with gravity influence (for subjects able to control weight bearing of their limb segments). All individual movements are prompted by a therapist, then attempted by the trainee, and might be completed to the extent individually needed by a therapist coupled with the patient's intention to move. Feedback is given by therapists as knowledge of performance (KP), that is, the degree as to which selective innervation and movement could be executed (in the intended joint, e.g., shoulder, elbow, forearm, wrist, or fingers) by a patient during the prompted attempt to perform the specific movement requested.

The following aspects of training implementation are specific for the situation with humanoid robot-led training: participants receive a first introductory session with a human therapist where they learn to know and how to perform the standardized training (AAT or ABT), its tasks, focus of motor control, and sequence of events. During this introductory session, the human therapist also notes and decides on individualizations indicated for either the AAT or the ABT that will then be used as prescription for the digital therapy system E-BRAiN.

For this research, the therapeutic training was led by the humanoid robot ("robot") during the consecutive nine sessions providing therapeutic interaction as implemented in the digital system based on both training standards and individualization algorithms. For safety reasons and to step in if needed, all humanoid robot-led sessions were accompanied by the supervising staff ("therapist"). Since the robot cannot provide physical assistance, but serves as a social agent only (providing therapeutic interaction), participants receiving the ABT were given physical assistance as needed by a "helper." The helper was not a trained therapist, but similarly used the instructions provided by the robot.

The two scenarios for humanoid robot-led therapy are depicted in Figure 2 (A, AAT; B, ABT).

2.5 Therapeutic context

Participants received their therapy as either outpatients at the University Medical Centre Greifswald or inpatients (sub-acute rehabilitation) in the BDH-Klinik Greifswald, in rooms with typical equipment for rehabilitation therapy, and the timing of their daily study-related therapy adapted to their individual schedules.

2.6 Analysis of the therapeutic interaction

Therapy sessions were videotaped, and all therapeutic interactions (information provision, feedback, and bond-related interaction) were documented offline both in terms of their frequency of occurrence and time used for the respective type of interaction during therapy sessions with standardized criteria using the instrument THER-I-ACT.

Using the instrument THER-I-ACT, various types of therapy-related communication interactions performed by therapists can be assessed with a high inter-rater reliability (Platz et al., 2021a). In addition, the thematic fields and categories of therapeutic interaction as defined by the instrument comprehensively cover the types of interaction that occur in therapeutic sessions. This is also true for situations where therapy is led by a humanoid robot (Platz et al., 2023).

For both the robot- and human therapist-led therapy, the therapeutic interaction during the first session with the respective agent (i.e., robot or human therapist) was analyzed; for the robot-led therapy, the last (9^{th}) session of daily training with the robot was analyzed in addition.

For the sessions with a humanoid robot, any additional therapeutic interaction spontaneously provided by the supervising staff or human helper needed to provide physical assistance (ABT only) was also documented.

2.7 Statistical analyses

Baseline characteristics and therapy assignment (i.e., ABT or AAT) are presented using descriptive statistics, that is, mean and standard deviation (s.d.), or count and relative frequency as indicated, for both the group receiving therapy using the digital therapy system E-BRAiN and the group receiving therapy in the conventional setting with a human therapist, respectively. Statistical analyses for baseline differences between these groups were performed using two-way chi-square tests or two-sample (independent group) t-tests as indicated; for t-tests, the equality of variances for the two groups had been tested with F tests; t-tests for equal or unequal variances had been used accordingly.

Humanoid robot, supervising staff, and helper interaction on day 1 is reported as mean across subjects for each type of therapy (i.e., ABT and AAT, resp.) as descriptive statistics. Effects of time (day 1 vs. day 9) on the humanoid robot interaction were analyzed by repeated-measures analysis of variance together with the between-subject factor type of therapy (ABT vs. AAT). The between-subject effect of the agent (humanoid robot vs. human therapist) was analyzed together with the factor therapy (ABT vs. AAT) by analysis of variance (ANOVA).

2.8 Sample size calculation

The statistical corroboration of bigger intergroup differences (effect size f = 0.5) with a pre-defined alpha error probability of 0.05 and power (1 – beta error probability) of 0.80 required a sample of 34 participants; to corroborate statistically (alpha error probability 0.05, power 0.80) at least substantial changes of humanoid robot behavior over time (effect size f 0.40), a sample size of 15 participants in the subgroup with robot-led therapy was necessary (Faul et al., 2013).

3 Results

3.1 Participants

Data of 17 stroke survivors receiving arm rehabilitation sessions (i.e., ABT [n = 9] or AAT [n = 8]) using a humanoid robot as a therapeutic agent over a course of nine sessions and 21 other stroke survivors receiving arm rehabilitation sessions (i.e., ABT [n = 6] or AAT [n = 15]) in a conventional 1:1 therapist–patient setting were used for the purpose of this study.

TABLE 1 Study population characteristics (*n* = 38).

	Robot therapy (*n* = 17)			Human therapist (*n* = 21)			P
	Mean/sd, n (%)	Min–max, n (%)	n	Mean/sd, n (%)	Min–max, n (%)	N	
Age (mean/sd, min–max)	62.4/14.3	36–81		65.0/9.2	49–80		0.5110 (t)
Sex (female, male) (n (%))	11 (65%)	6 (35%)		6 (29%)	15 (71%)		0.0259 (chi)
Stroke type (ischemic, ICH) (n (%))	14 (82%)	3 (18%)		18 (86%)	3 (14%)		0.7775 (chi)
Affected brain (left, right) (n (%))	6 (35%)	11 (65%)		11 (52%)	10 (48%)		0.2922 (chi)
Time post-stroke (weeks) (mean/sd, min–max)	86/115	3–367		212/315	8–1158		0.1006 (t)
NIHSS (0–42)(mean/sd, min–max)	4.6/2.1	1–9		6.4/4.8	2–18		0.1454 (t)
Barthel Index (0–100)(mean/sd, min–max)	79/18	35–100		92/10	70–100		0.0132 (t)
HADS (0–42)(mean/sd, min–max)	12.3/5.9	6–25	16[1]	10.6/7.0	2–27	20[1]	0.4407 (t)
FM Arm[a] (0–66) (mean/sd, min–max; n)	20.6/6.7	12–30	9	31.3/9.8	20–49	6	0.0244 (t)
BBT[b] (blocks/minute) (mean/sd, min–max; n)	32.5/11.6	18–44	8	38.3/11.3	17–58	15	0.2622 (t)
Type of therapy (ABT[a], AAT[b])	8	9		6	15		0.1265 (chi)

AAT , arm ability training; ABT, arm basis training; BBT, Box and Block Test; chi, *p*-value for the two-way chi-square test; FM Arm, Fugl–Meyer Arm Motor score; HADS, Hospital Anxiety and Depression Scale; ICH , intracerbral hemorrhage; NIHSS, National Institute of Health Stroke Scale; t, *p*-value for the two-sample (independent group) t-test.
Superscript letters (AAT[a] and ABT[b]) indicate the different types of therapy and how they relate to both the treated syndromes and the tests used for baseline assessment, respectively.
[a]One participant in each group did not want to disclose personal emotional information.

The study population (and both sub-groups) showed a considerable age distribution, both genders, different types of stroke etiology, a considerable variability of time post-stroke ranging from a few weeks to years, and mild-to-moderate neuro-impairment (NIHSS) (Brott et al., 1989) and neuro-disability (Barthel Index) (Mahoney and Barthel, 1965), as well as emotional distress (HADS) (Snaith, 2003). Similarly, within the sub-groups with either mild or moderate-to-severe arm paresis, the degree of arm and hand motor (dys) function varied considerably (comparing BBT and FM Arm scores, respectively) (Fugl-Meyer et al., 1975; Mathiowetz et al., 1985; Platz et al., 2005).

Accordingly, the sample might well present the variation typically seen in stroke survivors seeking neurorehabilitation services and, hence, challenges for the therapeutic system to address and adapt therapeutic interaction to diversified individual needs during rehabilitation therapy sessions.

Differences noted between the two sub-groups were a higher percentage of female participants in the subgroup receiving robot-led therapy and, on average, more pronounced neuro-disability (lower BI scores) and more severe motor impairment (FM Arm, group with moderate-to-severe arm paresis) in the group receiving robot-led therapy (comparing Table 1).

3.2 Therapeutic interaction

3.2.1 Pattern of the therapeutic interaction by the humanoid robot, supervising staff, and a helper

The pattern of therapeutic interaction as provided by the humanoid robot included episodes of provision of information, feedback, and bond-related interaction (compare Table 2). The therapeutic interaction varied markedly with the type of training (ABT or AAT) as warranted clinically and intended (comparing, also, Tables 3, 4 including statistical analyses for factor "therapy").

Overall, information provided by the humanoid robot included treatment-goal-oriented communication, training specifications, and instructions. Treatment-goal-oriented therapeutic interaction was characterized by a few more extended explanatory communication episodes. By far, the most frequently observed therapeutic interaction had been brief instructions, both for the ABT and AAT, while being both more frequent and shorter for the ABT compared to AAT. Training specifications (how the training is structured and how it might work) had been observed with the AAT only as a single longer explanation period per training session.

Feedback had only been observed with AAT and was provided as KR, mostly presented in a neutral manner and at times combined with positive social stimuli.

Bond-related interactions were also not infrequently documented, fell in the category "showing interest in the person treated" (e.g., asking the patient whether she or he is ready to continue), and were observed more frequently during AAT sessions.

The therapeutic interaction by a supervising therapist was comparatively infrequent, mostly observed in AAT sessions, mainly as additional instructions and some bond-related activity (in categories showing interest in the other person and responsivity).

Interaction by a helper for physical assistance (ABT only) was again much less frequent than interaction episodes by the humanoid robot and included mainly instructions, some feedback as KP, and not infrequently showing interest in the other person.

TABLE 2 Ther-I-Act observations: Therapeutic interaction by the humanoid robot, supervising therapist, and helper (day 1) (*n* = 17).

Themes and individual aspects	Humanoid robot (mean)				Supervising therapist (mean)				Helper (ABT only) (mean)	
	ABT (*n* = 9)		AAT (*n* = 8)		ABT (*n* = 9)		AAT (*n* = 8)		ABT (*n* = 9)	
	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti
1. Provision of information										
a. Treatment goal	4.6	227	2.0	140	0.1	< 1	0	0	0	0
b. Training specifications	0	0	1.0	290	0	0	0	0	0	0
c. Instructions	388	1859	145	1352	2.1	8	30	131	42.8	93
2. Feedback										
a. Knowledge of performance (unless corrective),	0	0	0	0	0.1	< 1	0.6	< 1	4.4	4
b. KP and positive social stimuli	0	0	0	0	0.4	< 1	0	0	1.2	1
c. KP and negative social stimuli	0	0	0	0	0	0	0	0	0	0
d. Corrective KP (cKP)	0	0	0	0	0	0	0	0	0	0
e. cKP and positive social stimuli	0	0	0	0	0	0	0	0	0	0
f. cKP and negative social stimuli	0	0	0	0	0	0	0	0	0	0
g. Knowledge of result	0	0	35.9	313	0	0	0.9	1	0	0
h. KR and positive social stimuli	0	0	4.3	34	0	0	0.1	< 1	0	0
i. KR and negative social stimuli	0	0	0	0	0	0	0	0	0	0
3. Motivational interactions										
a. Other than KP or KR	0.9	7	2	13	0	0	0.5	2	0.3	< 1
4. Bond										
a. Showing interest in person	16.7	118	44.5	289	1.2	19	4	30	12.9	29
b. Personal aspects (therapist)	0	0	0	0	0	0	0	0	0	0
c. Responsivity	0	0	0	0	0.1	< 1	5.4	16	0.8	1
d. Conflict solving	0	0	0	0	0.1	4	0	0	0.1	< 1
5. Other types of interaction	0	0	0	0	0.3	1	0.5	2	0.4	2
6. Presence (concentration) and engagement (treating person) (0–10)	5		5		8.9		9.3		9.9	
7. Focussed attention and engagement (patient) (0–10)	8.3		8.8							
Length of the therapeutic session (minutes)	77		107							

ABT, arm basis training; AAT, arm ability training; Fr, frequency of occurrence of the therapeutic interaction within the session (count) rounded to one decimal; Ti, time used for the therapeutic interaction within the session (in seconds) rounded to full seconds; KP, knowledge of performance; KR, knowledge of result.

3.2.2 Humanoid robot interaction—Its changes across sessions

The pattern of therapeutic interaction by the humanoid robot and its changes across sessions are presented in Table 3.

On the first day, one characteristic of the humanoid robot's therapeutic interaction was a considerable degree of information provision. As therapy progressed, patients became more knowledgeable about the training and were given less information provision (frequency and time allocated), while information was still offered by the humanoid robot as an option. As a consequence, more time was available for executing training tasks and led to more instructions.

For AAT, a small shift from "neutral" knowledge of the result feedback to the feedback associated with positive social stimuli (given with greater improvements within or across sessions) was observed from day 1 to day 9 of humanoid robot-led therapy indicating even better progress on day 9.

Presence and engagement rating for patients did not change from day 1 to day 9 indicating a high degree of focused attention and engagement performing the training tasks both from the beginning and being persistent over the course of daily therapy with a humanoid robot.

3.2.3 Pattern of the therapeutic interaction by the humanoid robot compared to human therapists providing the same type of treatment

Generally speaking, the pattern of the therapeutic interaction by the humanoid robot and human therapists providing the same type of treatment was fairly comparable with regard to the provision of information, feedback, and bond-related interaction (Table 4).

A closer look, nevertheless, documented differences for the therapeutic interaction by the humanoid robot and human therapists. A slightly more treatment-goal-related interaction (ABT) by the humanoid robot agent was observed, that is, comments regarding the training with reference to individual baseline scores and training goals. With humanoid robot therapy, less-frequent (repeated) instructions for individual training movements (ABT), no knowledge of performance (KP) feedback

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TABLE 3 **Ther-I-Act observations: Variation of the therapeutic interaction by the humanoid robot with therapy and over time (*n* = 17).**

Themes and individual aspects	Day 1 of therapy (mean)				Day 9 of therapy (mean)				Effect (*P* [F-test])			
	ABT (*n* = 9)		AAT (*n* = 8)		ABT (*n* = 9)		AAT (*n* = 8)		Therapy		Day	
	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti
1. Provision of information												
a. Treatment goal	4.6	227	2.0	140	2.6	75	2.0	72	**<.0001**	**0.0041**	**<.0001**	**<.0001**
b. Training specifications	0	0	1.0	290	0.8	17	0.8	27	**0.0005**	**<.0001**	**0.0294**	**<.0001**
c. Instructions	388	1859	145	1352	430	1962	156	805	**0.0001**	**0.0007**	**0.0138**	**<.0001**
2. Feedback												
a. Knowledge of performance (unless corrective)	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
b. KP and positive social stimuli	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
c. KP and negative social stimuli	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
d. Corrective KP (cKP)	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
e. cKP and positive social stimuli	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
f. cKP and negative social stimuli	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
g. Knowledge of result	0	0	35.9	313	0	0	34.6	314	**<.0001**	**<.0001**	0.3726	0.9598
h. KR and positive social stimuli	0	0	4.3	34	0	0	5.3	38	**<.0001**	**<.0001**	0.3811	0.6499
i. KR and negative social stimuli	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
3. Motivational interactions												
a. Other than KP or KR	0.9	7	2	13	0.4	6	1.6	14	**<.0001**	**0.0045**	**0.0184**	0.9588
4. Bond												
a. Showing interest in person	16.7	118	44.5	289	17.3	115	50.9	304	**<.0001**	**<.0001**	**<.0001**	0.4360
b. Personal aspects (therapist)	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
c. Responsivity	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
d. Conflict solving	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
5. Other types of interaction	0	0	0	0	0	0	0	0	n.a.	n.a.	n.a.	n.a.
6. Presence (concentration) and engagement (treating person) (0–10)	5.0		5.0		5.0		5.0		n.a.		n.a.	
7. Focussed attention and engagement (patient) (0–10)	8.3		8.8		8.4		8.9		0.5283		0.3474	
Length of the therapeutic session (minutes)	77		107		74		68		0.0853		**<.0001**	

ABT, arm basis training; AAT, arm ability training; Fr, frequency of occurrence of the therapeutic interaction within the session (count) rounded to one decimal; Ti, time used for the therapeutic interaction within the session (in seconds) rounded to full seconds; KP, knowledge of performance; KR, knowledge of result; *p*-values correspond to F statistics based on type III sums of squares of ANOVA. Bold values denote *p*-values < .05.

TABLE 4 Ther-I-Act observations: Variation of the therapeutic interaction by agent and type of therapy (day 1 of therapy) (n = 38).

Themes and individual aspects	Human interaction (mean)				Robot interaction (mean)				Effect (P [F-test])			
	ABT (n = 6)		AAT (n = 15)		ABT (n = 9)		AAT (n = 8)		Agent		Therapy	
	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti	Fr	Ti
1. Provision of information												
a. Treatment goal	1.5	225	1.3	124	4.6	227	2.0	140	**<.0001**	0.6365	**<.0001**	**0.0002**
b. Training specifications	1.2	80	1.4	75	0	0	1.0	290	**0.0032**	**0.0029**	**0.0112**	**<.0001**
c. Instructions	567	1970	159	1055	388	1859	145	1352	**0.0244**	0.3182	**<.0001**	**<.0001**
2. Feedback												
a. Knowledge of performance (unless corrective)	108	146	6.1	13	0	0	0	0	**<.0001**	**<.0001**	**<.0001**	**<.0001**
b. KP and positive social stimuli	84.7	129	3.7	10	0	0	0	0	**<.0001**	**<.0001**	**<.0001**	**<.0001**
c. KP and negative social stimuli	0	0	0.1	< 1	0	0	0	0	0.4801	0.4801	0.5548	0.5548
d. Corrective KP (cKP)	1.0	6.0	0.7	1	0	0	0	0	**0.0119**	0.1030	0.6804	0.2169
e. cKP and positive social stimuli	0	0	0	0	0	0	0	0				
f. cKP and negative social stimuli	0	0	0	0	0	0	0	0				
g. Knowledge of result	0	0	82.5	219	0	0	35.9	313	**0.0001**	**0.0036**	**<.0001**	**<.0001**
h. KR and positive social stimuli	0.2	< 1	42.9	108	0	0	4.3	34	**0.0001**	**0.0044**	**0.0001**	**<.0001**
i. KR and negative social stimuli	0	0	0	0	0	0	0	0				
3. Motivational interactions												
a. Other than KP or KR	0.2	< 1	3.4	8	0.9	7	2.0	13	0.4074	**0.0033**	**0.0019**	**0.0011**
4. Bond												
a. Showing interest in person	8.8	43	35	75	17	118	44.5	289	**0.0005**	**<.0001**	**<.0001**	**<.0001**
b. Personal aspects (therapist)	0	0	0.8	11	0	0	0	0	**0.0435**	0.0618	0.0889	0.1159
c. Responsivity	9.0	42	44.9	157	0	0	0	0	**0.0011**	**0.0003**	**0.0446**	**0.0443**
d. Conflict solving	0.3	5.5	0.3	4	0	0	0	0	0.0546	0.1037	1.0000	0.8524
5. Other types of interaction	0.5	4.3	1.6	9	0	0	0	0	**0.0007**	**0.0068**	0.0882	0.3691
6. Presence (concentration) and engagement (treating person) (0–10)	9.0		8.8		5.0		5.0		**<.0001**		0.5950	
7. Focussed attention and engagement (patient) (0–10)	9.5		8.3		8.3		8.8		0.6730		0.3700	
Length of the therapeutic session (minutes)	71		81		77		107		**0.0006**		**0.0001**	

ABT, arm basis training; AAT, arm ability training; Fr, frequency of occurrence of the therapeutic interaction within the session (count) rounded to one decimal; Ti, time used for the therapeutic interaction within the session (in seconds) rounded to full seconds; KP, knowledge of performance; KR, knowledge of result; p-values correspond to F statistics based on type III sums of squares of ANOVA. Bold values denote p-values < .05.

(ABT), and less knowledge of result (KR) feedback (AAT) (human therapist spontaneously provided not only summary KR but also additional immediate KR) were given. The robot showed more episodes of interest in the other person (e.g., asked "are you ready?") while a human therapist presumably perceived such information more frequently without having to ask. The humanoid robot lacked responsivity to spontaneous cues by patients (a fact that did, however, not lead to a necessity to solve conflicts). Overall, the robot was rated as less "engaged and present" by an independent offline rater compared to a human therapist, and it "did its job well," but was perceived and rated not to act as close/attentive to patients' behavior and needs as human therapists did. Patients training with a humanoid robot, nevertheless, showed similarly focused attention and engagement compared to patients having therapy sessions with a human therapist. Therapeutic sessions were somewhat longer with a robot (as intended) resulting in substantially long therapeutic sessions.

4 Discussion

Stroke survivors who participated in this research all had a need for arm rehabilitation, but were otherwise diverse with regard to their characteristics including gender, age, type of and time post-stroke, degree of overall disability (mild to moderate), and emotional distress (comparing Table 1). Collectively, the study population and its sub-groups receiving human- or humanoid robot-led therapy represented the typical range of characteristics that therapists encounter when providing stroke rehabilitation. Also, the sub-groups of stroke survivors receiving therapy by a human therapist or the robot-led therapy were largely comparable. If anything, the participants in the robot group had slightly more pronounced neuro-disability on average and, hence, might have generated a somewhat more challenging therapeutic situation (comparing Table 1).

In addition, the therapeutic situation (outpatient or inpatient scenario) was comparable to other regular rehabilitation treatments offered in medical centers.

Given both the study population characteristics and the therapeutic situation, the study context resembled regular treatment scenarios for stroke rehabilitation well and, therefore, promotes the ecological validity of the data generated; that is, the observations made can be considered relevant for routine clinical practice.

The pattern of the therapeutic interaction as provided by the humanoid robot included episodes of provision of information, feedback, and bond-related interaction (comparing Table 2) and while sharing similarities varied, nevertheless, across therapies (i.e., ABT and AAT, respectively; for statistical analyses, we compare Tables 2–4).

The humanoid robot addressed the issue of an individual treatment goal, explained the mechanism of action of therapy extensively (AAT), provided frequent brief instructions, intermittently feedback as knowledge of results (AAT), and showed interest in the treated person's situation (e.g., whether a patient was ready to continue with the next exercise).

The helper who provided physical assistance with weight bearing and movement of the more severely affected arm when needed (ABT only) and who was not a therapist, but based her or his activities on the system's instructions and prompts, added spontaneously further instructions (e.g., "you need to …") and communication episodes that showed interest in the other person (e.g., "are you ready?"). As a consequence, the supervising therapist contributed very little additional therapeutic interactions in ABT sessions while similarly adding spontaneously further instructions and communication episodes that showed interest in the other person (e.g., "are you ready?") during AAT sessions (without a helper being present). Taken together, these observations indicate that the humanoid robot covered the therapeutic interaction by and large sufficiently. During these humanoid robot-led therapy sessions, the human person being closest to the patient receiving therapy (i.e., the helper with ABT and supervising therapist with AAT) still occasionally spontaneously stepped in, mainly providing additional instructions and addressing personal context issues (e.g., being ready to continue). The data cannot tell whether such interaction was mandatory for the session's success. At any rate, it seemed not necessary to solve any conflict of risk of discontinuation of the therapeutic sessions as this would have fallen into the corresponding interaction category (i.e., conflict solving) that was rarely ever observed.

Over time (comparing day 9 to day 1 of training with the humanoid robot), the stroke survivors needed less general information and, hence, had more time for executing training tasks. The humanoid robot adapted its behavior, provided less information (while still offering it), and executed more instructions accordingly (comparing Table 3). The measures for focused attention and engagement were at a high level (on average, between 8 and 9 on a scale from 0 to 10) and constant across sessions indicating that the training (ABT and AAT) and working with the humanoid robot intensively over 9 days were suitable to both induce and stabilize a high degree of focused attention and engagement among the treated stroke survivors. The observation is considered important since "neural repair therapy" meant to improve brain functions by specific and intensive training can only be successful if such attitudes can be achieved and maintained during training.

Finally, the research intended to compare the observed therapeutic interaction as provided by the humanoid robot in therapy session situations to the therapeutic interaction provided by human therapists providing the same type of therapy in a conventional 1:1 therapeutic setting. Here, the overall picture was that the humanoid robot's therapeutic interaction resembled the therapeutic interaction by human therapists well, and even differences between therapies were well matched. This is reassuring since the therapeutic system E-BRAiN was developed to lead through (daily) therapy sessions in an autonomous way with all communication and therapeutic interaction necessary.

Differences documented between the humanoid robot's and human therapists' therapeutic interaction are, nevertheless, worthwhile noting. It is considered a strength of the therapeutic system E-BRAiN that it links individual treatment goals with the training prescribed even slightly more frequently than human therapists do. Other differences are, however, related to technical limitations of the current technology used and algorithms implemented. So far, the system cannot sense limb movements or muscle innervation and, hence, cannot provide KP during ABT as humans can, based on their visual and tactile perception of innervation and movement attempts by patients, and similarly is limited to provide additional instructions based on partial completion of movements. The system also cannot recognize and interpret spontaneous verbal and non-verbal communication cues provided by patients and cannot be responsive to them. Indeed, related research indicated that stroke survivors consider it a relevant disadvantage that currently available socially interactive humanoid robot systems do not possess human abilities, such as the ability to hold a conversation and to express or understand emotions (Dembovski et al., 2022). Future further development of the system might help to overcome some of these limitations.

It is, however, of importance to note in this context that focused attention and engagement by patients during the training sessions observed were high and comparable for both humanoid robot- and human therapist-led therapy sessions, not only when the series of training sessions commenced (day 1) but also after nine daily sessions (day 9). Thus, any differences in the therapeutic interaction observed did not translate in a different behavioral attitude of patients, and even somewhat longer therapeutic sessions could be realized.

The digital therapy system E-BRAiN uses a socially interactive humanoid robot as technology and established AI that provides (A) professional therapeutic training knowledge for both arm rehabilitation and neglect therapy based on types of therapy with evidence to support their effectiveness for recovery post-stroke (in this research, demonstrated for ABT and AAT), (B) effectively leads through (daily) therapy sessions in an autonomous way with all communication and therapeutic interaction necessary, and (C) individualizes all activities based on individual data (e.g., clinical characteristics, results of assessment, and therapeutic goal).

The systems that had been developed so far equally demonstrated that socially interactive humanoid robots can be used for arm rehabilitation after stroke in a clinically meaningful and acceptable way (Koren et al., 2022).

Here, we add to our knowledge that such a system can be set up in a way that not only generates a sequence of tasks to be practiced but also provides the means for a series of largely autonomous humanoid robot-led therapeutic sessions with all types of therapeutic interaction necessary. Furthermore, the system E-BRAiN integrates personalized information that adapts the system's behavior to individual needs, ongoing training behavior, and progress. This is even true for different forms of therapies that can be prescribed as needed based on individual clinical circumstances. All these refined aspects of AI integration led to the overall comparability of therapeutic interaction during humanoid robot-led sessions using E-BRAiN with interaction observed during conventional human therapist-led therapeutic sessions providing the same type of therapy.

The research, thus, provides evidence that AI using humanoid robot technology together with algorithms to implement complex rehabilitation therapy assistance can achieve scenarios that resemble human–patient interactions, comprehensively represent the work flow of therapeutic sessions for training-based therapies with strong evidence to support their clinical effectiveness, and might, therefore indicate a way to establish more specific and intensive "neural repair" therapy.

Given the increasing global societal need to combat neuro-disabilities, such solutions could play a pivotal role once established, when proven to be acceptable to people with neuro-disabilities in need for rehabilitation and to be clinically safe and (cost-)effective.

Perceived from a broader perspective, robot technology that may be used for rehabilitation purposes might provide either specific therapeutic interaction (as investigated here), register training behavior by sensor technology, and/or provide physical assistance as needed. Ideally, rehabilitation technology could be equipped with some or all of these characteristics, depending on specific use cases.

Indeed, mechanical robot technology providing physical assistance as needed for repetitive practice has effectively been introduced in neurorehabilitation and helps to enhance intensive repetitive practice schedules, especially among people with severe paresis (e.g., after stroke) (Mehrholz et al., 2018). First applications for human care also demonstrate that humanoid aspects can be integrated into applications that provide physical assistance, for example, for daily care or physical therapy practice (Mukai et al., 2010; Jevtić et al., 2019; Miyake et al., 2022). With regard to therapy they do, however, lack comprehensive social interaction that supports a rehabilitation technology to be used without close supervision by human therapists.

In the research reported, a comprehensive social therapeutic interaction by a humanoid robot implemented in and used with a therapeutic system has been characterized and shown to be largely comparable to the human therapeutic interaction when providing the same types of therapy. While the system can also record training progress for some aspects (e.g., the time used for AAT tasks to be completed), but so far not for others (e.g., selective motion for the various joints as practiced during the ABT), it cannot provide physical assistance, an aspect that is compensated for by a human helper in the context of the ABT (while not needed for the AAT, a training for people with mild arm paresis).

For the future, it is well conceivable that systems could be developed that comprehensively integrate specific therapeutic interaction (as investigated here), register training behavior by sensor technology more comprehensively (e.g., motion tracking), and/or provide physical assistance as needed.

Data availability statement

The datasets presented in this article are not readily available because the data presented may only be used by personal and for purposes that had been agreed upon in advance in writing by participants. Requests to access the datasets should be directed to thomas.platz@uni-greifswald.de.

Ethics statement

The studies involving human participants were reviewed and approved by the Ethikkommission der Universitätsmedizin Greifswald. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

TP designed and wrote the manuscript. All authors participated in the preparation and implementation of the robot-led therapy and critically revised the manuscript for intellectual content.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Functional improvement of patients with Parkinson syndromes using a rehabilitation training software

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Introduction: Individuals with Parkinsonian disorders often face limited access to specialized physiotherapy and movement training due to staff shortages and increasing disease incidence, resulting in a rapid decline in mobility and feelings of despair. Addressing these challenges requires allocating adequate resources and implementing specialized training programs to ensure comprehensive care and support. Regarding these problems, a computer software was invented that might serve as an additional home-based extension to conventional physiotherapy.

Methods: The trial took place in a rehabilitation center where every patient received equivalent treatment apart from the training program that was set up to be investigated over 3 weeks. Seventy four Patients were included and randomized between two intervention and one control group. Intervention group 1 (IG1) trained with the computer-based system two times a week while Intervention group 2 (IG2) received five training sessions a week. Using the markerless Microsoft Kinect® camera, participants controlled a digital avatar with their own body movements. UPDRS-III and Clinical measurements were performed before and after the three-week period.

Results: Patients in all groups improved in UPDRS-III pre and post intervention whereas reduction rates were higher for IG1 (−10.89%) and IG2 (−14.04%) than for CG (−7.74%). Differences between the groups were not significant (value of ps CG/IG1 0.225, CG/IG2 0.347). Growth rates for the arm abduction angle were significantly higher in IG1 (11.6%) and IG2 (9.97%) than in CG (1.87%) (value of ps CG/IG1 0.006 and CG/IG2 0.018), as was the 5-steps-distance (CG 10.86% vs. IG1 24.5% vs. UG2 26.22%, value of ps CG/IG1 0.011 and CG/IG2 0.031).

Discussion: The study shows the beneficial effects of computer-based training and substantiates the assumption of a similar impact in a home-based setting. The utilized software is feasible for such interventions and meets with the patient's approval. Group dynamics seem to have an additional supporting effect for the aspired objective of improving mobility and should be seen as an essential aspect of video games in therapy.

KEYWORDS

Exergame, Parkinson's disease, rehabilitation, Kinect, physiotherapy, home-based, markerless, movement training

Introduction

The treatment of patients with Parkinson's disease and other Parkinsonian disorders necessitates a comprehensive and multidimensional approach that incorporates medication, physiotherapy, ergotherapy, psychotherapy, and social assistance (1). Empowering patients with autonomy and self-determination in their battle against the disease, along with the pursuit of therapy effectiveness, serves as the driving force behind the development of an independent exercise therapy tailored to this specific group of patients.

Previous reviews have demonstrated the feasibility and mostly comparable effects of video games in the treatment and rehabilitation of individuals with various neurological disorders (2–4). However, the current availability and design of these gamified experiences primarily cater to healthy users, typically children or young adults. Consequently, individuals facing individual limitations due to disorders, mobility restrictions, and age often find themselves excluded from participating in these activities or utilizing them for medical treatment purposes. To address this issue, our group, comprising clinical doctors, rehabilitation physicians, and software engineers, undertook the endeavor of creating a camera-assisted exercise medium that allows this specific patient group to compensate for physical deficits associated with the disease within the comfort of their own homes.

Exergames, also known as exercise games, have demonstrated significant utility in the treatment of patients with Parkinsonian disorders (5). In line with this, a special virtual reality training game utilizing the Microsoft Kinect® camera was developed in collaboration with an experienced software company. This innovative approach combines the benefits of exergaming and virtual reality technology to provide a tailored and engaging exercise experience for individuals with Parkinsonian disorders. Accordingly, Canning et al. (6) highlight the increasing demand for virtual reality technology in rehabilitation settings and the need for further research in this area.

Building upon a previously conducted pilot study (7), this clinical trial was conducted to investigate the benefits of the system within a cohort of patients with Parkinsonian disorders, taking into account the scarcity of controlled studies on the subject (8) and the insufficient training dosage (9) or sample size (10) in previous research. Furthermore, this study aimed to specifically examine the hypothesis that a higher frequency of additional computer-based training would result in greater improvement in mobility and movement among patients. Additionally, research has shown that training with video games such as Kinect®-based exercises can enhance cognitive aspects (11, 12), which offers the prospect of similar benefits in the domains of cognition and motivation.

Moreover, this approach represents a potential response to the increasing incidence of Parkinson's disease resulting from demographic changes, as well as the shortage of physiotherapists (13). By establishing a home-based treatment model, one-on-one care becomes less necessary. Additionally, it is widely acknowledged that physical exercise through exergaming can improve both quality of life and balance in patients with PD (14). Besides, specific phenomena such as Pisa syndrome in PD (15) and freezing of gait (16) can and should be addressed through diverse exercises. Furthermore, these innovative applications of telemedicine can help reduce costs associated with travel and therapy itself (17). Although these challenges are not new, they have gained significant attention, particularly in light of the coronavirus pandemic.

Abbreviations: CG, Control Group; DBS, Deep Brain Stimulation; IBM, International Business Machines Corporation; IG1, Intervention Group 1; IG2, Intervention Group 2; LCD, Liquid-crystal display; L-Dopa, Levodopa; MDS, The International Parkinson and Movement Disorder Society; PD, Parkinson's disease; TV, Television; UPDRS, Unified Parkinson's Disease Rating Scale.

Methods

Design

Inclusion, exclusion, and attrition

The trial was designed following a prospective, randomized, and controlled protocol. The investigation was conducted at a rehabilitation hospital focused on neurology patients and certified as a rehabilitation center for Parkinsonian diseases. Primarily, 87 potential patients were identified of which 74 were eventually included (Figure 1). Patients were included if they had a rehabilitation treatment of at least 3 weeks, had a diagnosis of at least one neurological movement disorder, were of legal age, and had capacity. Exclusion criteria were severe visual impairments, severe dementia, and inability to walk. During the course of the study, there was one instance of attrition where a patient was unable to complete the full 3-week protocol. This occurred because the patient experienced recurring syncopes and orthostatic instability unrelated to this trial, requiring an acute referral to another hospital for further medical intervention. As a result, the data from this particular case had to be excluded from the analysis to maintain the integrity and consistency. By removing the incomplete data from the analysis, the overall validity of the study's findings can be preserved.

Patient selection

The selected patients were randomized using a matched pairs design dividing them into three groups: Intervention group 1 and Intervention Group 2 (IG1 and IG2) containing 25 and 24 patients, respectively, and a control group (CG) containing 25 patients. To ensure balanced groups and minimize potential bias, a merging process was implemented to assign patients to triplets based on their baseline characteristics at a rough estimate. Within each triplet patients were then randomly assigned to one of the three treatment groups helping to distribute any potential confounding factors equally among the groups and enhancing the validity of results. Baseline characteristics including age, number of patients with DBS system, Hoehn and Yahr score, duration of disease, and duration of rehabilitation treatment were similar between each group (Table 1). There was no further group stratification based on DBS.

The purpose of the study, the associated risks, potential outcomes, and the anonymized usage of data were thoroughly explained to the patients who were assigned. The informed consent process was conducted, and the patients provided their consent in written form, indicating their understanding and agreement to participate. It was also made clear that they had the right to refuse participation or withdraw from the trial at any point without the need to provide reasons. By providing comprehensive information and obtaining informed consent, the study adhered to ethical guidelines and ensured that the patients were well-informed participants in the research process.

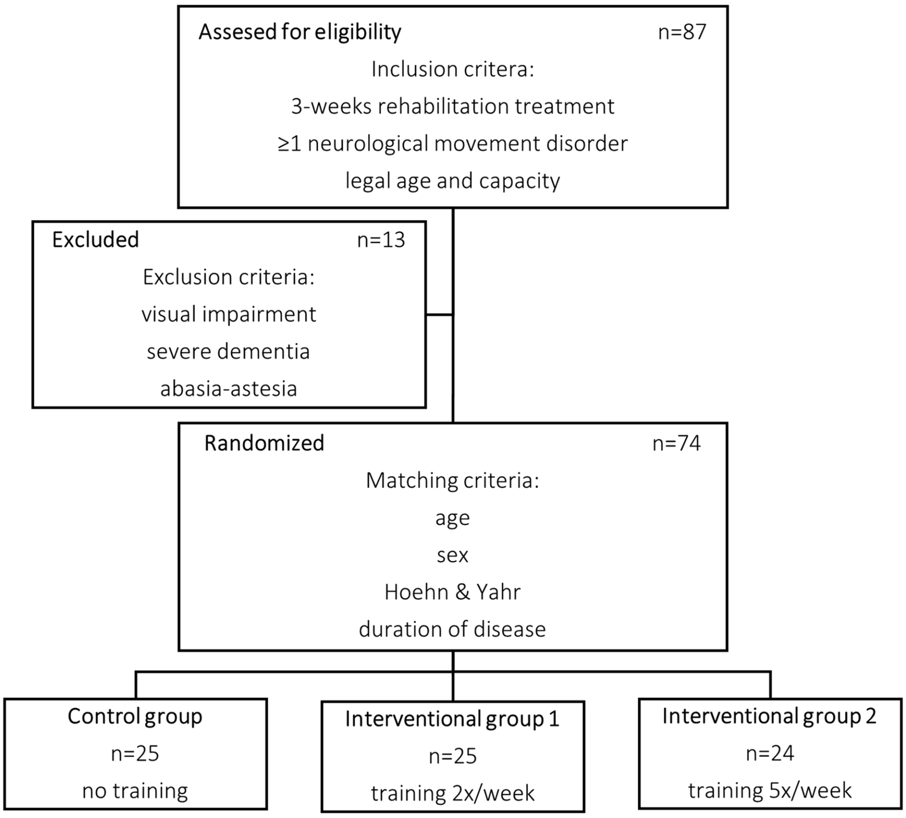

FIGURE 1
Flow chart of patient selection.

TABLE 1 Baseline data.

	Control group (Group 1, no training)	Interventional group 1 (Group 2, training 2x/week)	Interventional group 2 (Group 3, training 5x/week)	*p*-value
No. of participants	25 [m 16, f 9]	25 [m 15, f 10]	24 [m 15, f 9]	
Age (years, mean)	72.92 (± 9.65)	73.56 (± 9.28)	72.71 (± 8.00)	0.570
No. of participants with DBS	3 (12%)	3 (12%)	4 (17%)	0.860
Hoehn and Yahr score (mode)	3 [1–4]	3 [1–4]	3 [1–4]	0.760
Duration of disease (years, mean)	8.64 (± 6.00)	8.32 (± 8.03)	7.83 (± 5.87)	0.785
Duration of rehabilitation treatment (weeks, width)	3 [3–6]	3 [3–4]	3 [3–5]	0.785
Levodopa equivalent dose pre (mg, mean)	603.44 (± 331.64)	582.08 (± 393.71)	652.58 (± 369.91)	0.716
Levodopa equivalent dose post (mg, mean)	641.52 (± 360.18)	649.12 (± 371.85)	719.58 (± 377.07)	0.701
Levodopa dose pre (mg, mean)	394.00 (± 223.17)	339.00 (± 239.91)	373.96 (± 250.60)	0.551
Levodopa dose post (mg, mean)	389.00 (± 207.43)	364.00 (± 246.34)	389.67 (± 245.15)	0.839

Training scheme

An idealized training scheme was set up to distribute training days balanced throughout the total intervention time of 3 weeks. Meanwhile, all patients continued receiving standard rehabilitation physical therapy and medical optimization in terms of medication and non-medication assistance. Patients in the IG1 trained twice weekly, either on Mondays and Thursdays or on Tuesdays and Fridays resulting in a total of six training days. Patients in the IG2 trained every day within the week (Mondays to Fridays), thereby receiving 15 days of exercise in total. Patients in the CG were treated with conventional rehabilitation therapy only.

L-Dopa equivalents

To exclude the adaption of medication as a disruptive factor for the interpretation of changes in the physical agility of patients, L-Dopa medication was assessed pre- and post-intervention. L-Dopa equivalent doses were calculated to ensure comparability. Following the introduction of safinamide in 2015 and opicapone in 2016, the previously used conversion (18) was extended (19) and utilized in this trial. Table 1 shows that all three groups increased their L-Dopa equivalent dose whereas there is no difference between each of them in both pre- and post-assessment. It was not feasible to conduct a more precise registration of On–off-Status and exact medication administration per day and per patient. Therefore, these specific details were not recorded or included in the study's data collection process.

Training system

Development

The inventory process and the intended purpose of this system were arranged in concordance with the latest suggestions by the MDS Task Force on Technology (20). While inventing the training system, primary body movement disorders such as gait and balance disorders, camptocormic posture and gait abnormalities, rigidity, akinesia, tremor, and fine motor skills disorders were identified, most of which were integrated into the conceptual planning. Specific movement patterns were defined which are to be practiced with the support of the therapy system and which counteract the above-mentioned disorders in a targeted manner. Particular attention was paid to stretching the upper body and getting the patient to stand up and sit down addressing greater walking and standing stability and the speed of movement. Another requirement for the system was the recognition of essential symptoms via marker-free sensor systems. Despite its approved usage for diagnostical purposes (21, 22), it was not to be assumed at the current time of processing, that resting, action and postural tremors of the hands could be recorded with the Microsoft® Kinect sensor system. To avoid fatigue and other adverse reactions, the duration of the training had to be adjusted accordingly and break times were considered. Cognitive exercises are integrated into the system to bridge them.

Specifications

The established training system is based on the markerless sensing Microsoft Kinect® camera which can easily be connected to any computer system and runs with the developed training software without additional software needed. Moreover, the setup requires a simple LCD monitor such as a TV set that most people possess in their homes. For the training session, the patient has to stand in front of the camera at a distance of two to four meters and needs enough space to move their arms freely. No additional software or hardware is needed which makes the system very feasible and safe to use. The software includes guiding instructions for the whole game, as well as previews for all the movements the patients have to perform within the different games making it completely self-explanatory. Symptoms of Parkinsonian diseases tend to progress with time showing a successive decline in movement amplitude and speed (23). To counteract these developments the games were designed to condition a faster and wider sequence of movement. Similar concepts of progressive training have been used by Vieira de Moraes Filho et al. (24) eventually improving brady- and akinesia over time. In an overall game time of approximately 20 min, patients play four mini-games (Figure 2) with a focus on upper limb movement and the rise from a chair targeting the extension of the range and speed of motion. Table 2, therefore, comprises the intended purposes for every specific movement trained by one of the four exercises. Additionally, the software records the height of the avatar and the time needed to trigger each following object within the different games to assess the progress of the player afterwards.

Data collection

Measurements

Clinical examinations and measurements included in this study were made by the conducting staff and by well-trained physiotherapists. To objectify the findings, the change in the Unified Parkinson's Disease Rating Scale (part III) of The International Parkinson and Movement Disorders Society (MDS-UPDRS-III) was used as the primary outcome variable. This scale is well established for the assessment of motoric symptoms of patients with Parkinsonian diseases (25). The data collection was conducted following an idealized schedule with an observation period of 3 weeks (21 days) for every patient. Clinical measurements and MDS-UPDRS-III were taken before the first and after the last training session of the interventional groups and on the first and last day of the three-week study term of the CG, respectively. The assessments mentioned are routine procedures conducted during admissions to the rehabilitation center where the trial took place. To ensure the accuracy and consistency of the assessments, the team of physiotherapists responsible for conducting the UPDRS-III assessments received comprehensive training from experienced neurologists. As a result, they were highly proficient in administering the tests and were well-versed in the evaluation process. The UPDRS-III assessments were performed on an individual basis and in a single-blinded manner. This means that the conducting physiotherapists were unaware of both the training status and group assignment of each patient. This approach helped minimize potential bias and ensured the objectivity of the assessments.

To extend the evaluation to record elusive changes in mobility that are not covered by the findings of the MDS-UPDRS-III assessment, further clinical measurements and tests were applied. The patients were asked to stand straight and stretch out their arms as far above their heads as possible. Then, the distance from the fingertips to the floor was measured to investigate the maximal erecting of the body. This is meant to address the ability to reach out to objects that are placed overhead which is a very important skill in day-to-day life. Apart from that, the greatest abduction angle of both arms was documented by taking photographs and was later quantified using the graphical software GIMP®. The same software was used to evaluate the angle of camptocormia as a marker for the severity of the posture impairment. Additionally, patients had to do a 5-step-walking test which primarily focused on freezing symptoms after the initial "start" command and which was meant to assess gait impairments. Therefore, time and distance were recorded. Due to the nature of the study and the involvement of the main researcher in both the training sessions and data

FIGURE 2
Game situation for the Coconuts, Balloons, Balls and Stars Games (from top left to bottom right).

collection, maintaining blinding for data acquisition of these additional measurements was not feasible. However, efforts were made to ensure objectivity and consistency in the data collection process.

Statistics

Statistical analysis was conducted using IBM SPSS Statistics 25.0® (Armonk, United States). The normal distribution of the outcome parameters was assessed using the Shapiro–Wilk test, given the small sample size. Depending on the nature of the data, either parametric or non-parametric test procedures were employed. Specifically, the Mann–Whitney U-test and Kruskal-Wallis test were used for continuous variables, while the Pearson's Chi^2 test was applied for categorical variables. A significance level of 0.05 was used for all test procedures.

Results

All groups showed improvements regarding MDS-UPDRS-III and clinical measurements within the observed period.

MDS-UPDRS-III

Patients presented with insignificantly different MDS-UPDRS-III at baseline (value of ps CG/IG1 0.214, CG/IG2 0.418) between the two Interventional Groups (26.08 IG1, 27.92 IG2) and the Control Group (31.0 CG). Improvements in motion result in lower MDS-UPDRS-III which is why calculated growth rates are negative. The reduction rate (Figure 3) in the IG1 (−10.89%) was higher and in the IG2 (−14.04%) nearly double as it was in the CG (−7.74%) which correlates with an absolute reduction (Figure 4) of −2.84 (IG1), −3.92 (IG2) and – 2.4 (CG), respectively (Table 3). Nevertheless, these findings were not significant (value of ps CG/IG1 0.225, CG/IG2 0.347).

TABLE 2 Description of games and addressed movements.

Name of exercise	Movement trained	Purpose
Coconuts	Upper limbs, abduction/ elevation	Reach out to objects above the head
Stars	Lower limbs, hip and knee extension	Stand up from a chair
Balls	Upper limbs/upper body, abduction/retroversion and rotation	Reach out to objects behind the shoulder, stabilize the body
Balloons	Upper limbs, anteversion	Reach out to objects in front

Clinical measurements

Accordingly, the clinical measurements present similar findings (Figure 5). While there could not be identified significant differences in height and 5-step-time, the interventional groups differed significantly from the control group in terms of abduction angle and 5 steps distance (Table 4). For the abduction angles the growth rate in the CG was only 1.87% compared to 11.60% in the IG1 and 9.97% in the IG2 (value of p CG/IG1 0.006, CG/IG2 0.018). Likewise, growth rates in the 5-step-distance doubled with 24.50% in the IG1 and 26.22% in the IG2 compared with 10.86% in the CG (value of p CG/

IG1 0.011, CG/IG2 0.031). Further, the improvement of camptocormia was better in the interventional groups as well (−13.34% IG1 / -14.63% IG2 vs. -6.38% CG) but lacking in significance.

Kinect® data

As previously mentioned, the Microsoft Kinect® camera can track and record parameters within the game. That made it possible to assess the influence of the training through the system itself accordingly and to compare these findings to the other results as a further system evaluation. As the intervention was only performed on the IG1 and IG2, differences between these two groups were analyzed (Figure 6). At baseline, there were no significant differences between the groups regarding the means of the duration needed to trigger subsequent objects. On the last day of the training, patients in the IG2 became significantly faster in the "Coconut game" and in the "Overall game time" than in the IG1, whereas similar improvements seen in the "Star game" were tightly insignificant (Table 5).

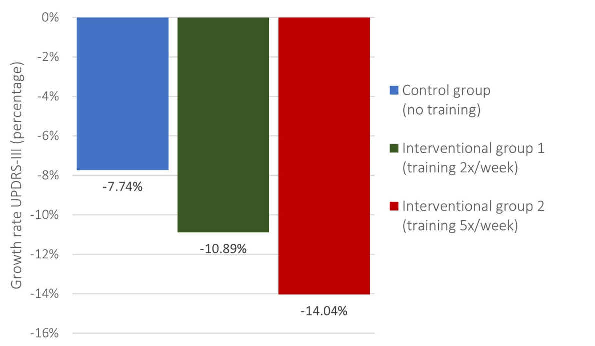

FIGURE 3
MDS-UPDRS-III growth rates.

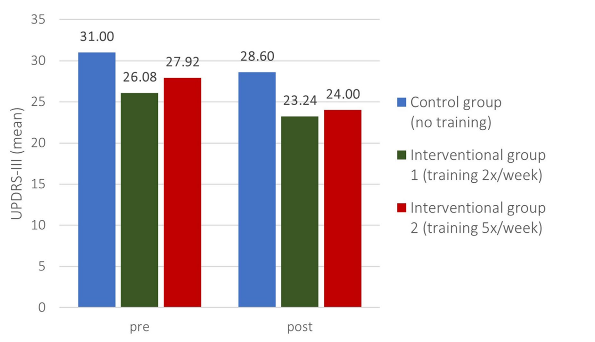

FIGURE 4
MDS-UPDRS-III pre- and post-intervention.

Discussion

Outcome

The results of this study provide strong evidence supporting the positive impact of rehabilitation treatment on the movement abilities of patients with Parkinsonian diseases. These findings further support previous research indicating the beneficial effect of inpatient rehabilitation settings (26). All groups exhibited improvements in the assessed attributes over the observed period, indicating the effectiveness of various aspects of the treatment, including medication, physiotherapy, sociopsychological dynamics, and Kinect®-based training.

MDS-UPDRS-III and clinical examination evaluation

Combining conventional rehabilitation treatment with computer-based training sessions demonstrated greater advancements in movement abilities. While the statistical significance of improvements in MDS-UPDRS-III and clinical examinations varied, it can be assumed that the use of the MS Kinect®-based training system can enhance mobility for patients with Parkinson's disease. Specifically, the training system had a positive effect on the movement range of the upper limbs, step length, and posture of the patients. Higher frequency of additional training correlated with greater improvements, with the interventional groups outperforming the control group and Intervention Group 2 showing even better results than Intervention Group 1. Weaker improvements in abduction degree and 5-steps-time in IG2, compared to IG1, can be attributed to some patients in IG2 undergoing joint replacement procedures, which limited their limb mobility independent of Parkinson's disease symptoms.

Kinect® data evaluation

The Kinect® system records were found to be valid and consistent with other findings. The fact that IG2 demonstrated increasingly faster completion of game quests compared to IG1 supports the assumption of a direct positive correlation between

TABLE 3 MDS-UPDRS-III pre- and post-intervention, MDS-UPDRS-III growth rate.

	Control group (Group 1, no training)	Interventional group 1 (Group 2, training 2x/week)	Interventional group 2 (Group 3, training 5x/ week)	Value of p (Group 1 vs. group 2)	Value of p (Group 1 vs. group 3)
UPDRS III pre (mean)	31.00 (± 16.51)	26.08 (± 14.82)	27.92 (± 14.56)	0.214	0.418
UPDRS III post (mean)	28.60 (± 17.66)	23.24 (± 15.47)	24.00 (± 14.43)	0.225	0.347
Growth rate	−7.74%	−10.89%	−14.04%		

mobility improvement and training frequency. These results underscore the feasibility, safety, and benefits of using the Kinect® system to assist physiotherapy. However, further enhancements to the software are necessary to tailor it to individual disease levels and enhance patient motivation for daily training sessions.

Group dynamics

One noteworthy aspect of training games, as observed in this study, is the positive impact of group dynamics reported by the staff. This factor may have influenced the beneficial effects of the game therapy on the patients and warrants further investigation. The enjoyment derived from this novel form of rehabilitation training positively impacted motivation for each subsequent session, aligning with findings from previous studies (27–29). Additionally, considering the theoretical prevention of Parkinson's disease (30), moderate physical exercise should be recommended to younger, healthy individuals due to the epidemiological correlation between higher physical activity and lower incidence of the disease (31).

Conditioning

Another contributing factor to the observed improvements was patient conditioning through repeated use of the same training games. Patients derived satisfaction and motivation from noticing their performance improvements, fostering a sense of pride in their achievements. This, in turn, contributed to the group dynamics mentioned earlier and a heightened drive for better results in each subsequent training session. Similarly, a study by Schootemeijer et al. (32) reported significantly higher adherence to exercise in highly motivated patients. This suggests that motivated individuals are more likely to maintain long-term exercise habits, leading to consolidated effects and sustained benefits. These observations may also be attributed to improvements in working memory and cognitive function (33) as well as enhancements in functional connectivity between the cortex and basal ganglia (34).

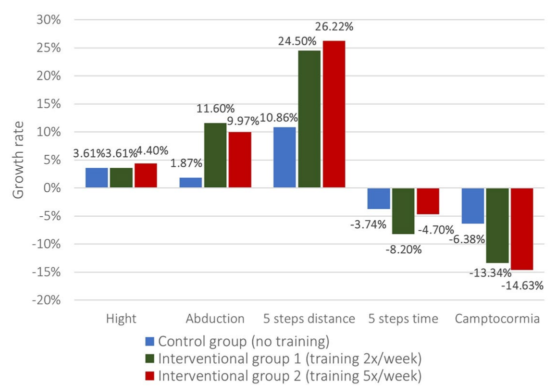

FIGURE 5
Growth rates of changes in clinical measurements.

Limitations

Several limitations affected the consistency of statistical significance, including the relatively small sample size and adjustments in medication during the study period. Changes in L-Dopa administration, in particular, could have introduced some inequality. However, the lack of significance in the slight differences observed between the groups indicates that serious deviations were unlikely. Nevertheless, the increased L-Dopa doses in each group probably had a proportional effect on mobility improvement, highlighting the importance of optimizing medication in the treatment of patients with Parkinsonian diseases. Furthermore, the limited number of patients with deep brain stimulation (DBS) hampers the analysis of any potential effects of DBS, which will be explored in future research. Studies with a similar 3-week design have shown consistent findings, and long-term maintenance of exercises for several years has demonstrated a relative stabilization of impairing symptoms (35). This suggests that continuous engagement in exercise therapy can have prolonged benefits. Additionally, due to the three-week observation period, this study was unable to assess positive long-term effects on Parkinson's disease progression, as observed in other therapeutic studies (36, 37). Indeed, research with a comparable design but longer follow-up periods has demonstrated significant effects as early as 12 weeks (38), providing further support for the presumed efficacy of the presented intervention.

Summary

In summary, this study demonstrates the beneficial effects of computer-based training and supports the assumption that similar

TABLE 4 Growth rates of changes in clinical measurement.

(Growth rates, mean)	Control group (Group 1, no training)	Interventional group 1 (Group 2, training 2x/week)	Interventional group 2 (Group 3, training 5x/week)	*p*-value (*Group 1 vs. group 2)*	*p*-value (*Group 1 vs. group 3)*
Hight	3.61	3.61	4.4	0.236	0.133
Abduction	1.87	11.6	9.97	**0.006**	**0.018**
5 steps distance	10.86	24.5	26.22	**0.011**	**0.031**
5 steps time	−3.74	−8.2	−4.7	0.377	0.984
Camptocormia	−6.38	−13.34	−14.63	0.648	0.244

Significant findings are highlighted in bold.

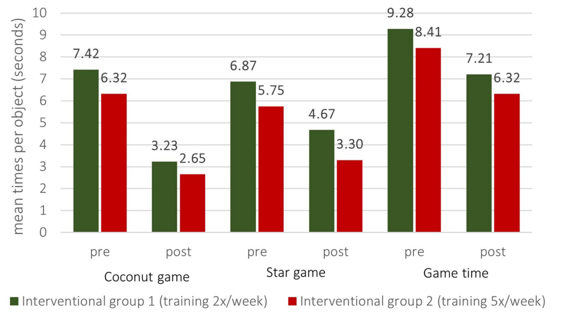

FIGURE 6
Means of time to trigger subsequent objects pre- and post-intervention per group.

TABLE 5 Means of time to trigger subsequent objects pre- and post-intervention per group.

	(Means)	Interventional group 1 (Group 2, training 2x/week)	Interventional group 2 (Group 3, training 5x/week)	*p*-value
Coconut game	Pre	7.42	6.32	0.575
	Post	3.23	2.65	**0.036**
Star game	Pre	6.87	5.75	0.447
	Post	4.67	3.30	0.063
Game time	Pre	9.28	8.41	0.327
	Post	7.21	6.32	**0.013**

Significant findings are highlighted in bold.

impacts can be achieved in a home-based setting. The software and hardware used in the intervention were feasible and well-received by the patients. Group dynamics emerged as an essential aspect of video game therapy, offering additional support for the goal of improving mobility.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Ethikkommission der Westsächsischen Hochschule Zwickau. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MB handled the clinical implementation of the training system, conducted the training sessions with patients, gathered the data, wrote the article and created the tables and figures. RM provided technical expertise with the training system, helped in organizing the data collection, and conducted the data analysis. PT was involved in the conceptual planning of the training system, provided facilities for patient enrolment, gave clinical advice throughout the trial conduction, and critically revised the article. EG was involved in the conceptual planning of the training system and its clinical implementation. CM was involved in the conceptual planning of the training system and its clinical implementation. DW was involved in the conceptual planning of the training system, determined the study design, edited the article after critical revision and organized the trial conduction. RG co-created the training system, was involved in its conceptual planning and clinical implementation, provided technical expertise and critically revised the article. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Augmented feedback modes during functional grasp training with an intelligent glove and virtual reality for persons with traumatic brain injury

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Introduction: Physical therapy is crucial to rehabilitating hand function needed for activities of daily living after neurological traumas such as traumatic brain injury (TBI). Virtual reality (VR) can motivate participation in motor rehabilitation therapies. This study examines how multimodal feedback in VR to train grasp-and-place function will impact the neurological and motor responses in TBI participants (n = 7) compared to neurotypicals (n = 13).

Methods: We newly incorporated VR with our existing intelligent glove system to seamlessly enhance the augmented visual and audio feedback to inform participants about grasp security. We then assessed how multimodal feedback (audio plus visual cues) impacted electroencephalography (EEG) power, grasp-and-place task performance (motion pathlength, completion time), and electromyography (EMG) measures.

Results: After training with multimodal feedback, electroencephalography (EEG) alpha power significantly increased for TBI and neurotypical groups. However, only the TBI group demonstrated significantly improved performance or significant shifts in EMG activity.

Discussion: These results suggest that the effectiveness of motor training with augmented sensory feedback will depend on the nature of the feedback and the presence of neurological dysfunction. Specifically, adding sensory cues may better consolidate early motor learning when neurological dysfunction is present. Computerized interfaces such as virtual reality offer a powerful platform to personalize rehabilitative training and improve functional outcomes based on neuropathology.

KEYWORDS

traumatic brain injury, virtual reality, motor rehabilitation, sensory feedback, hand grasp, physical therapy

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1 Introduction

Trauma to the brain can severely impair motor function to perform activities of daily living (Colantonio et al., 2004). For affected individuals, rehabilitation of hand function, especially reaching and grasping, is critical for environmental access (Chaabani et al., 2014). Physical therapy is a primary option to rehabilitate hand function; however, traditional therapy involves intensive and repetitive movement training (Connell et al., 2018). Feelings of rigor during training are naturally detrimental to efficient gains in function; thus, methods fostering greater engagement are needed to overcome the monotony of physical practice (Lohse et al., 2013). Newer approaches to physical therapy are seeking to utilize advanced technologies, such as virtual reality (VR) (Howard, 2017) and instrumented wearables (Simone et al., 2007), to motivate participation in therapy.

Computerized technology, especially virtual reality, is increasingly employed in motor rehabilitation to facilitate greater motivation and to provide customizable training options, including enhanced feedback (Merians et al., 2006). Computerized interfaces can provide robust movement guidance (Gorgey, 2018) and leverage cognitive elements of physical training that can accelerate motor learning after neurological traumas (Mulder and Hochstenbach, 2005). Given their vast programmable features, virtual reality environments are well suited to personalize rehabilitative training that maximizes user engagement and functional outcomes based on neural processes (Holden and Todorov, 2002). Integrating advanced technologies with motor rehabilitation creates a user-computer interface that can motivate with colorful and immersive environments while also providing real-time guidance using enhanced sensory-driven feedback to facilitate motor recovery (Mulder and Hochstenbach, 2005). Thus, virtual environments can optimize motor learning by manipulating training conditions, e.g., guidance cues, for a given user profile, e.g., pathological features, to broadly affect motivational, cognitive, motor, and sensory learning mechanisms (Levin et al., 2015).

Augmented feedback with sensory cues informing individuals about performance achievements or errors during training is proven to enable motor learning (Sigrist et al., 2013). Augmented feedback activates sensory modalities (e.g., visual, audio, haptic) to guide performance during training (Sigrist et al., 2013). With "multimodal" augmented feedback, more than one sensory modality is activated concurrently to hasten motor learning trajectories by broadening the areas of neural activation and exceeding neural activation thresholds earlier during repeated practice (Sigrist et al., 2013; Seitz and Dinse, 2007). Thus, multimodal feedback in VR motor rehabilitation training is a promising approach to recovering motor function after neurological traumas. Our lab has shown how motor performance is sensitive to features in augmented feedback (Sanford et al., 2020) using computerized interfaces for either motion (Sanford et al., 2021) or myoelectric control tasks (Sanford et al., 2022; Walsh et al., 2021).

Still, it remains unclear if persons with neurological damage, such as traumatic brain injury (TBI), respond similarly to augmented feedback approaches as neurotypicals. Given disturbed brain connectivity after TBI (Hayes et al., 2016), the ability to process sensory cues (Folmer et al., 2011) and subsequently apply them with functional capabilities (Ciccarelli et al., 2020) can be compromised. Another potential challenge in utilizing augmented sensory feedback with TBI is a possible deficiency in synchronizing cues with the functional task being practiced (Ghajar and Ivry, 2008). Accurately inferring times of cues relative to task actions is especially critical to ensure motor training with augmented feedback will be effective.

Our lab has previously developed and verified the potential of training with an intelligent glove system capable of providing augmented sensory cues for a functional grasp task while also inducing a sense of agency (Liu et al., 2021). Sense of agency, or perception of control, is a cognitive measure highly associated with motor function (Moore, 2016). Intentional binding is an implicit measure of agency (Moore and Obhi, 2012), which manifests from the compression of one's perception of the time between a voluntary action and an expected outcome. Our lab has shown positive relationships between implicit measures of agency and movement performance (Nataraj et al., 2020a; Nataraj et al., 2020b; Nataraj and Sanford, 2021; Nataraj et al., 2022) and seeks to leverage such connections for better rehabilitation approaches.

In our training paradigm with the glove system, we facilitate a sense of agency through intentional binding by progressively reducing the delay between the user's action of a "secure" grasp and the outcome of sensory cues from the onboard modules. The glove system includes onboard force and flex sensors and a processor for an artificial neural network to identify secure grasp, as detailed in (Liu et al., 2021). Participants are cued about their action of securely grasping an object based on sensory-activation modules (visual: LED light, audio: beeper) onboard the glove and then proceed to complete the grasp-and-place task. During training, there is a progressive reduction of the delay between the action and consequential sensory cue to stimulate a perception of greater binding and, therefore, stronger feelings of agency. In our previous study with the intelligent glove system (Liu et al., 2021), we reported that neurotypicals demonstrated improved performance of a grasp-and-place task using "binding" feedback during training compared to no feedback or immediate (no delay) feedback. However, it was unclear if participants with neurological impairment may respond similarly, given potential challenges with discerning timing or processing augmented sensory feedback in VR.

The current study seeks to establish how participants with neurological dysfunction (i.e., TBI) will respond using this glove system when augmented sensory feedback is provided in the following ways: 1) progressively binding feedback to actions during training as done in (Liu et al., 2021), 2) further enhancing the sensory cues through VR, and 3) comparing the effects between providing unimodal (audio only) and multimodal (audio plus visual) cues. Responses in the presence of TBI will be characterized along domains of neural activation (electroencephalography, EEG), functional motor performance, and muscular engagement (electromyography, EMG) and compared against neurotypical responses. We hypothesized that multimodal feedback in VR will support greater neural (EEG) and muscular (EMG) activation and improve performance (reduced motion pathlengths, reduced completion times) of a grasp-and-place task for persons with TBI.

2 Materials and methods

2.1 Participants

Persons with TBI (n = 7) were recruited for a funded study (New Jersey Health Foundation, Research Grant PC 53-19) and tested at Kessler Foundation. These participants signed an informed consent form approved by the Institutional Review Board (IRB) at Kessler. The committee, composed of persons not associated with a given study, reviews and approves all human research studies at Kessler annually. They assure the safety of study participants, patients and healthy volunteers, including the use of clear language in the consent form. These participants were diagnosed as having moderate-to-severe TBI with upper extremity deficits.

Participants with TBI were classified based on the TBI Model Systems National Database (Dijkers et al., 2010), where one of the following criteria must be met: (a) loss of consciousness for 30 min or more; (b) posttraumatic anterograde amnesia for 24 h or more; (c) lowest Glasgow Coma Score (GCS) (Sternbach, 2000) in the first 24 h ≤ 15 (unless due to intubation, sedation, or intoxication); or (d) evidence of significant neurological injury on CT/MRI (e.g., subdural hematoma, cerebral contusion, subarachnoid hemorrhage). Severity was further defined using the following GCS score criteria: mild (14–15), moderate (9–13), or severe (3–8). Injury severity was confirmed from medical records when possible; in the absence of medical records, severity was determined by family member attestations of the length of loss of consciousness/coma.

Another group of neurotypical participants (n = 13) was recruited among a pool of students at Stevens Institute of Technology and compensated using funds from the Charles V. Shaefer, Jr. School of Engineering and Science at Stevens. These participants were tested at Stevens after signing an informed consent form approved by the Stevens IRB. The Stevens IRB is composed of members internal and external to the institution, and it reviews and approves all human research studies at Stevens annually. Neurotypical participants did not report nor indicate complications involving cognition or upper extremity function.

Study enrollment did not require participants to undergo clinical function assessments; thus, limited data were available to infer the degree of motor impairment for TBI participants. However, two participants were sampled from a participant pool having undergone timed tasks for the Wolf Motor Function tests (Lin et al., 2009). The average time score was 31 ± 13 s, which correlates to an upper-extremity Fugl-Meyer score of approximately 40 according to (Hodics et al., 2012), which denotes mild-to-moderate motor impairment (Woytowicz et al., 2017). Furthermore, the average maximum voluntary contraction (MVC) for EMG-recorded muscles of the TBI group was 72% ± 40% for the respective muscles of the neurotypical group. MVC exercises included index-thumb gripping (close- and open-grip directions) and wrist flexion-extension. Overall, we presume that TBI participants for this study have relatively high motor function.

2.2 Instrumented glove system to detect secure grasp

The glove system hardware (Figure 1) included a compression glove embedded with force (*Interlink Electronics*) and flex (*Spectra Symbol*) sensors across each digit, aligned on the palmar dorsal side, respectively. The sensors were connected to an instrumentation board (*Teensy*) programmed with *Arduino*. The board and wired connections were housed in a custom 3D-printed enclosure with a wrist-strapped mount. Sensory modules onboard the glove included an LED and sound beeper used for visual and audio cues in our previous study (Liu et al., 2021). The function of these sensor modules is now replaced (and enhanced) in this study using VR (details described in Section 2.3). The glove with onboard instrumentation has a mass of under 100 g. API code in *MATLAB®* (*Mathworks*) read sensor data via serial communication at 40 Hz and was processed on an *Intel* desktop computer (*Xeon®* 3.20 GHz, 32 GB RAM, *Windows 10 Pro*). The board is programmed to run a trained two-layer feedforward artificial neural network (Neural Network Toolbox, *MATLAB®* , *Mathworks*) to compute (predict) whether hand grasp upon an object is secure (or not) based on inputs from the onboard force and flex sensors. The network creation and training procedures are detailed in (Liu et al., 2021). During each training trial, the glove *1*) identifies the achievement of a "secure" grasp onto an object, *2*) informs the user by activating a feedback module, and *3*) facilitates agency via greater "binding" by progressively reducing the delay (from 1 to 0 s across all training trials) between grasp action and feedback cue. A surgical glove was placed over the sensor glove to ensure a better fit to the hand.

2.3 Experimental protocol

All participants donned our custom-built instrumented glove on their self-selected dominant side (left- and right-hand versions available) to perform a functional (grasp-and-place) task for all trials. At Stevens, neurotypical participants wore a 32-channel scalp-surface cap for EEG recording (*USBamp*, *g. tec*) and skin-surface EMG electrodes (*Delsys Trigno*) at hand and forearm muscles. EMG recordings were taken at the following seven muscle sites: flexor carpi radialis (proximal flexor), extensor carpi radialis brevis (proximal extensor), flexor digitorum superficialis (distal flexor), extensor digitorum communis (distal extensor), abductor pollicis brevis (thumb abductor, palmar-side recording), adductor pollicis (thumb adductor, dorsal-side recording). At Kessler, TBI participants wore a 64-channel scalp-surface cap for EEG recording (*actiCHamp Plus*, *BrainVision*) and seven EMG electrodes (*Power Lab/30 Series*) at the same locations as neurotypical participants. Protocols at Kessler and Stevens were identical except for the number of trials collected in each block (explained below).

The motor task for each trial entailed reaching and grasping a small cubic object, lifting it from an "Initial" location, and then moving and placing the object onto a "Target" location (Figure 2). Participants were asked to grasp the object with a precision pinch, i.e., using index finger and thumb (Nataraj et al., 2014). Participants with TBI were encouraged to adapt their grasp strategy as needed to perform the task successfully. However, all TBI participants could achieve a precision pinch grasp without

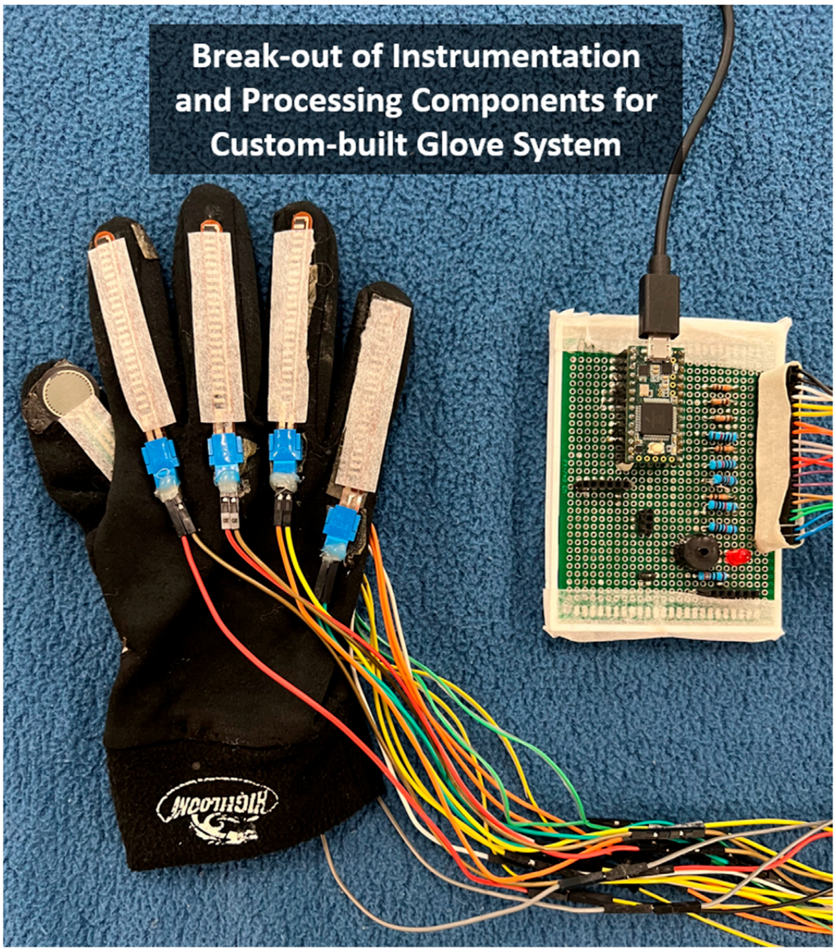

FIGURE 1
Instrumented glove includes force and flex sensors providing inputs to artificial neural network that predicts when secure grasp on object is achieved and triggers augmented sensory feedback cue. Note: Glove is right-handed shown from dorsal side with thumb inverted to show force-sensitive resistor on palmar side (i.e., thumb-pad).

discernible adaptation. Participants were informed that they were assessed for performance *primarily* on minimizing the object's motion pathlength and *secondarily* on placing it accurately on the designated target and completing the task promptly.

In adding VR feedback to our glove system, participants experienced mixed-mode reality. They manipulated a real object while viewing a VR environment (*Unity*) through a headset (*HTC Vive*) displaying virtual representations of the object and the gloved hand. These representations were identified and translated into VR using a motion controller (*LEAP*). Calibration procedures were performed to synchronize the positions of the virtual and real cubic objects and have them coincide with the participant's perspective at the start of each trial. Secure grasp was still detected based on glove sensor inputs to the onboard neural network processor.

In VR, the audio feedback was naturally enhanced when provided through the headset's earpiece. In addition, the visual cues were enhanced by having the entire virtual object change color (red to green) during secure grasp. Augmented feedback cues about secure grasp were only provided during training trials. During training, participants received augmented sensory feedback upon and during secure grasp in VR. Augmented feedback was delayed upon detecting a secure grasp. However, the delay progressively reduced from 1 to 0 s overall training trials to induce agency through binding (Moore and Obhi, 2012). The earpiece provided *unimodal feedback* as a singular beep ("audio cue"). The beep was short (100 m sec duration) with moderate tone and pitch. For *multimodal feedback*, the virtual object *additionally* changed color ("visual cue") from red to green. The color change activated concurrently with the audio cue, but it was persistently active during secure grasp and would inactivate (i.e., the virtual object turned red again) upon release of the object. Providing multimodal feedback in this way, i.e., persistent visual cue and audio with a single beep, was most effective (least distracting) to participants based on a series of pilot experiments to validate this training approach with neurotypicals initially (Liu et al., 2021).

In each session, a participant executed three blocks of trials: 1) an initial block of trials without feedback to establish baseline performance (i.e., "pre" training), 2) a block of trials to train with augmented feedback at progressively shorter time delay intervals (1–0 s) after "secure" grasp to induce binding, 3) a block of trials

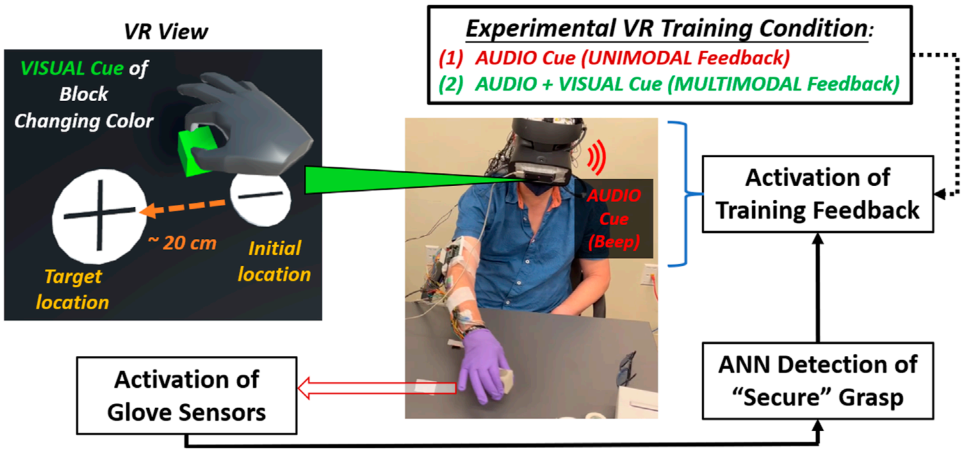

FIGURE 2
Flow diagram shown for experimental procedure for mixed-mode reality grasp-and-place task. Participant wears instrumented glove (under surgical glove) in grasping and moving cubic object while receiving augmented sensory feedback during training.

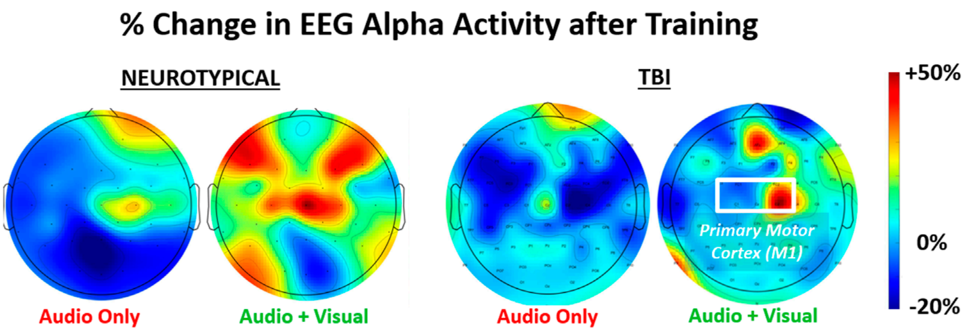

FIGURE 3
Representative relative change in regional brain activity (EEG alpha power) after feedback training of a grasp-and-place task. Results shown for neurotypicals and participants with traumatic brain injury (TBI) under two conditions of training with augmented sensory feedback (unimodal: audio only; multimodal: audio plus visual).

without feedback to determine effects after (i.e., "post") training. For pre/train/post blocks, neurotypical participants underwent 15/25/15 trials, respectively, and TBI participants underwent 25/50/25 trials, respectively. More trials were undertaken for TBI participants since clinical collaborators had suggested more trials would be better elicit an effect in this population. For neurotypical participants, we followed trial-level procedures according to our previous work with this glove system (Liu et al., 2021). The three blocks of trials were repeated for each of two different feedback conditions during the training block: 1) *unimodal feedback* (audio cues only), 2) *multimodal feedback* (concurrent audio and visual cues). These two training conditions were presented in random order for each participant session completed within a single day.

2.4 Data analysis

All metrics were computed as trial averages for each participant before determining the effects of the participant group (TBI versus neurotypical) or feedback condition (unimodal or multimodal). Metrics for performance included the 3-D motion pathlength of the cubic object being transported and the task completion time (i.e., the time the object is being moved from initial to target positions). In both cases, performance is better when the metric is lower. Participants consistently placed the object at the target location; thus, accuracy measures were not evaluated. Instead, the primary performance metric was computed as the object's motion pathlength while transported from initial to target locations, with completion time serving as a supplementary performance metric.

Neural activity was computed as EEG power in the alpha (8–12 Hz) and beta (13–30 Hz) bands. Additionally, EMG metrics were calculated as the overall mean amplitude across all seven muscles recorded and EMG-EEG coherence. EMG-EEG coherence was computed between an intrinsic hand muscle with the highest EMG amplitude for that participant group (abductor pollicis brevis for neurotypicals, abductor pollicis longus for TBI) and the EEG electrode corresponding to the M1 motor area. Different muscles expressing, on average, maximum EMG

TABLE 1 Mean baseline (pre-training) value for each metric of interest and mean relative percentage change from baseline after (post) training.

Metric	Mean baseline NT (*units*)	Mean baseline TBI (*units*)	Mean % change from baseline							
			NT-A	NT-AV	TBI-A	TBI-AV	NT	TBI	A	AV
EEG-alpha	(3.3 ± 8.8) E03	(2.2 ± 7.2) E03	−7.4 ± 43	57 ± 68	−3.7 ± 33.5	43 ± 15	25 ± 64	20 ± 35	−6.1 ± 38	52 ± 55
EEG-beta	(1.1 ± 2.6) E04	(0.6 ± 2.0) E04	−20 ± 40	97 ± 104	−25 ± 33	53 ± 27	39 ± 97	14 ± 50	−22 ± 36	78 ± 82
PERF-pathlength	34 ± 4.2 (*cm*)	34 ± 4.3 (*cm*)	−19 ± 3.3	21 ± 7.8	22 ± 14	−21 ± 15	0.7 ± 21	0.7 ± 26	−4.7 ± 22	6.1 ± 23
PERF-completion time	1.5 ± 0.4 (*sec*)	1.3 ± 0.4 (*sec*)	−20 ± 14	−4.7 ± 15	18 ± 29	−12 ± 20	−12 ± 16	2.9 ± 29	−6.4 ± 27	−7.3 ± 17
EMG-amplitude	4.4 ± 2.3 (mV)	1.4 ± 4.2 (mV)	−7.3 ± 14	−1.6 ± 9.5	−21 ± 33	6.4 ± 37	−4.4 ± 12	−7.4 ± 36	−11 ± 20	0.6 ± 20
EMG-M1 coherence	0.25 ± 0.015 (*unitless*)	0.25 ± 0.020 (*unitless*)	3.8 ± 6.1	−4.3 ± 5.3	1.2 ± 4.5	−2.5 ± 5.5	−0.3 ± 7.0	−0.7 ± 5.2	2.9 ± 5.6	−3.7 ± 5.3

Note: Percentage changes reported per participant group (NT, neurotypical; TBI, traumatic brain injury) and per feedback condition [A, audio only (unimodal); AV, audio plus visual (multimodal)].

TABLE 2 ***p*-values indicating if a post-training change in metric is significant ($p < 0.05$) in comparison to zero (1-sample *t*-test), between group-condition pairs (2-sample *t*-test), and within levels for each factor (2-way ANOVA, factors: participant group, feedback condition).**

Metric	1-Sample				2-Sample		2-way ANOVA	
	NT-A	NT-AV	TBI-A	TBI-AV	NT-A vs. NT-AV	TBI-A vs. TBI-AV	Participant group: TBI vs. NT	Feedback condition: A vs. AV
EEG-alpha	0.57	**0.019 (*t* = 2.8)**	0.80	**0.001 (*t* = 6.8)**	**0.027 (*t* = -2.6)**	**0.025 (*t* = -3.2)**	0.76	**1.3E-03 (F = 12)**
EEG-beta	0.21	**0.034 (*t* = 2.6)**	0.12	**5.4E-03 (*t* = 4.7)**	**0.029 (*t* = -2.7)**	**0.0028 (*t* = -5.5)**	0.31	**3.0E-04 (F = 18)**
PERF-pathlength	**8.8E-11 (*t* = -21)**	**6.7E-07 (*t* = 9.4)**	**6.9E-03 (*t* = 4.0)**	**0.011 (*t* = -3.6)**	**4.9E-11 (*t* = --21)**	**1.8E-04 (*t* = 8.2)**	0.99	0.13
PERF-comp. time	**2.6E-04 (*t* = -5.1)**	0.29	0.15	0.16	**0.020 (*t* = -2.6)**	**0.030 (*t* = 2.8)**	0.042	0.89
EMG-amplitude	0.077	0.56	0.22	0.72	0.28	0.10	0.70	0.095
EMG-M1 coherence	**0.046 (*t* = 2.2)**	**0.017 (*t* = -3.0)**	0.52	0.27	**8.8E-03 (*t* = 3.1)**	0.10	0.83	**6.0E-04 (F = 14)**

Note: p-values < 0.05 are bolded with t-stat or F-stat included.

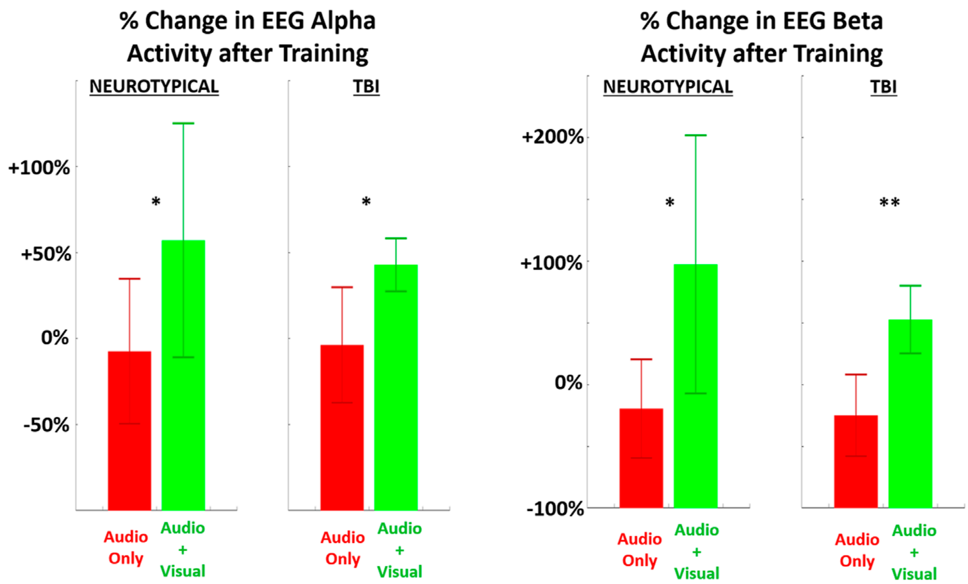

FIGURE 4
The relative (percentage) change in EEG power (LEFT = alpha band, RIGHT = beta band) in the performing grasp-and-place task is shown from before training (baseline) to after training with augmented sensory feedback. Results are compared between feedback conditions (unimodal: audio only; multimodal: audio plus visual) per participant group (neurotypicals, TBI). Note: *p < 0.05, **p < 0.01, ***p < 0.001 in comparing effects of feedback condition within each group.

amplitude suggests some variation in grip strategy between the neurotypical and TBI groups. However, the variations in grip are likely negligible given abductor pollicis muscles are still highly recruited and likely will reflect changes in EMG-EEG coherence primarily based on feedback training conditions, as designed.

The mean EEG power overall (across all channels) and within the alpha and beta frequency bands were analyzed using "EEGLAB" in MATLAB®. Mean values for EEG and EMG were computed within a time window that spanned one second before the achievement of secure grasp to one second after the release of the object. All metrics were evaluated as a percentage change from "pre" to "post" blocks to assess the effects of training.

The Kolmogorov–Smirnov test was applied to confirm sufficient normality of each data set to be analyzed by a parametric test. A two-way ANOVA was applied on each measure to determine the effects of the two main experimental factors: feedback condition (i.e., unimodal: audio only; multimodal: audio + visual) and participant group (i.e., neurotypical, TBI). A paired two-sample t-test was used for assessing the simple effects of feedback conditions on each measure within participant groups since identifying the potential impact of feedback conditions for clinical populations is of primary interest in this study. In addition, a one-sample t-test was applied for each pairing of group and feedback condition to determine whether a significant post-training change occurred from baseline (i.e., a non-zero % change). Finally, linear regressions were applied to verify dependent relationships between performance and EEG and whether significant linear trends existed in trial-by-trial changes of each measure within (during) the training block.

3 Results

Examples of brain (alpha power) activation plots are shown for each group (neurotypical, TBI) paired with a training feedback condition (unimodal, multimodal) in Figure 3. Relatively higher alpha power is grossly observable with multimodal feedback for both groups; however, the activation regions appear more diffuse with neurotypicals. For multimodal feedback in TBI, two areas of concentrated activation are evident, including one near the primary motor cortex (M1).

The mean values of the percentage changes (i.e., from pre-to post-training) for each metric and the overall mean value at baseline (i.e., pre-training) are provided in Table 1. It should be noted that baseline values were not significantly different between neurotypical and TBI groups for any metric. In addition, for each measure, the specific p-values for individual comparisons between feedback conditions within each group (2-sample t-test), non-zero change from baseline (1-sample t-test), and aggregate factor-level effects for group and training feedback condition (2-way ANOVA) are shown in Table 2. From 2-way ANOVA, only the EEG and EMG-EEG coherence metrics showed a significant factor-level difference and only for the factor of training feedback condition. This result further highlighted the need to examine the simple effects of feedback on each metric within each group to affirm the critical hypothesis of this study (i.e., the presence of neurological dysfunction will alter how multimodal versus unimodal feedback impacts brain activity, muscle engagement, and functional performance of a motor rehabilitation task). Thus, individual metric results are discussed further within the context of feedback conditions with each participant group in the bar plots shown in Figure 4 through 6.

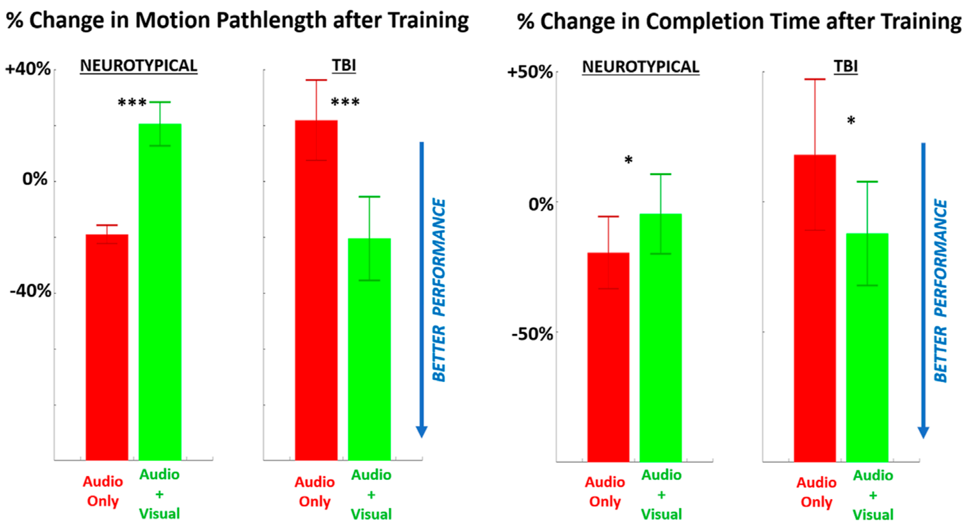

FIGURE 5
The relative (percentage) change in performance (LEFT = motion pathlength, RIGHT = completion time) in performing the grasp-and-place task is shown from before training (baseline) to after training with augmented sensory feedback. Results are compared between feedback conditions (unimodal: audio only; multimodal: audio plus visual) per participant group (neurotypicals, TBI). Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ in comparing effects of feedback condition within each group.

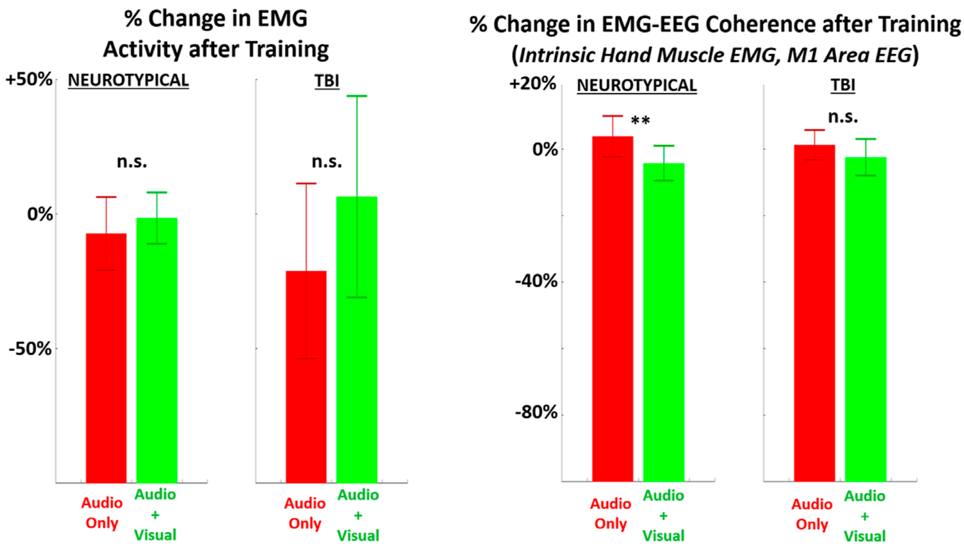

FIGURE 6
The relative (percentage) change in EMG metrics (LEFT = average EMG amplitude across all muscles recorded, RIGHT = EMG-EEG coherence between intrinsic hand muscle with highest amplitude and M1 brain area) in performing the grasp-and-place task is shown from before training (baseline) to after training with augmented sensory feedback. Results are compared between feedback conditions (unimodal: audio only; multimodal: audio plus visual) per participant group (neurotypicals, TBI). Note: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ in comparing effects of feedback condition within each group.

Significant post-training changes were observed in neurological activity (EEG power) within the alpha and beta bands after training with multimodal versus unimodal feedback (Figure 4). Again, results are expressed as the percentage change in each measure after training compared to before, i.e., at baseline. Neurological activity was significantly ($p < 0.05$) increased in both groups with multimodal feedback for both alpha and beta bands. This increase in activity with multimodal feedback is demonstrated as significant compared to unimodal feedback and from baseline. Unimodal feedback did not produce significant changes from the zero baseline (Table 2).

For performance, both metrics showed improvement (i.e., shorter pathlengths, shorter completion time) with multimodal feedback, compared to unimodal feedback (Figure 5), for the TBI group. However, these performance trends were reversed (i.e., performance worsened with multimodal feedback) for

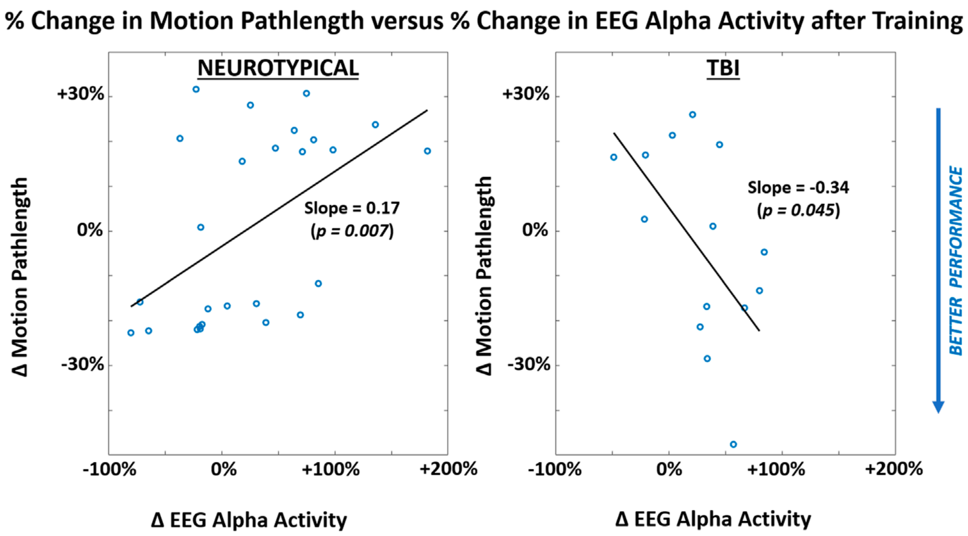

FIGURE 7
Correlations between participant-level mean values of performance metric (motion pathlength) and neural activity (EEG alpha power) within each participant group (LEFT = neurotypical, RIGHT = TBI). Results are shown for after training and pooled across both feedback conditions. Correlation represented through slope parameter for linear regression fitted to data. Slope magnitudes were assessed to be significantly non-zero ($p < 0.05$).

neurotypicals. Of further note, the change in motion pathlength was significantly different from zero (baseline) for every pairing of group and training condition. The change in completion time was significantly non-zero only for neurotypicals with unimodal feedback with significantly improved (reduced) completion time compared to baseline.

EMG metrics did not demonstrate significant differences in any case for persons with TBI (Figure 6). However, there was a significant difference in EMG-EEG coherence between training feedback conditions for neurotypicals. Furthermore, for neurotypicals, the unimodal feedback condition produced a significant increase in EMG coherence from baseline after training, but multimodal feedback produced a significant decrease in coherence.

When attempting to discover a correlation between performance and neural activity, a significant non-zero slope parameter with linear regression was observed in relating motion pathlength to EEG alpha activity separately for each participant group across both conditions (Figure 7). Notably, the TBI group demonstrated improved performance (reduced motion pathlength) with increased EEG alpha power. However, the neurotypical group showed worsened performance with increased EEG activity.

When examining trends in each metric during training trials, at least one significant difference was observed for each metric pending the specific group or training condition. For both feedback conditions, EEG metrics significantly increased across training trials in the TBI group (Figure 8). For performance metrics (Figure 9), significant improvements (reductions) were observed in completion time for all four group-condition pairs. Significant improvements were observed in motion pathlength only for TBI but with both feedback conditions, leaving non-conclusive trends in motion pathlength for neurotypicals with both conditions. For EMG (Figure 10), a significant reduction in EMG amplitude was observed for TBI and audio-only feedback. In contrast, a significant increase in EMG-EEG coherence was observed for TBI, but with multimodal feedback. Training trends for all remaining EMG cases were inconclusive. The specific slope and associated p-values are presented in Table 3.

4 Discussion

This study evaluated how varying the nature of augmented sensory feedback used for motor training with virtual reality can impact post-training changes in neurological activity, motor performance, and muscular engagement for a grasp-and-place task. The central experimental factor was cueing neurotypical and TBI participants about secure grasp with either unimodal (audio cue only) or multimodal (audio cue plus visual cue) feedback during each training repetition. Ultimately, we examined the effects of training with each feedback condition by comparing EEG power, motor task performance, and EMG measures immediately after (post) training compared to before (pre) training, serving as the comparative baseline for each participant. Our primary finding was that the effects broadly observed on these measures were unique depending on whether participants were neurotypical or had moderate-to-severe TBI.

Both groups exhibited increased EEG activity, in both alpha and beta bands, after training with multimodal feedback compared to unimodal feedback. More robust EEG responses are generally expected following more exposure to sensory stimulation (Teplan et al., 2006). However, the relative increases with TBI were larger than neurotypicals and may have impacted respective motor outputs accordingly. With multimodal feedback, there were contradictory findings in performance as TBI participants significantly improved (reduced) their average motion pathlength

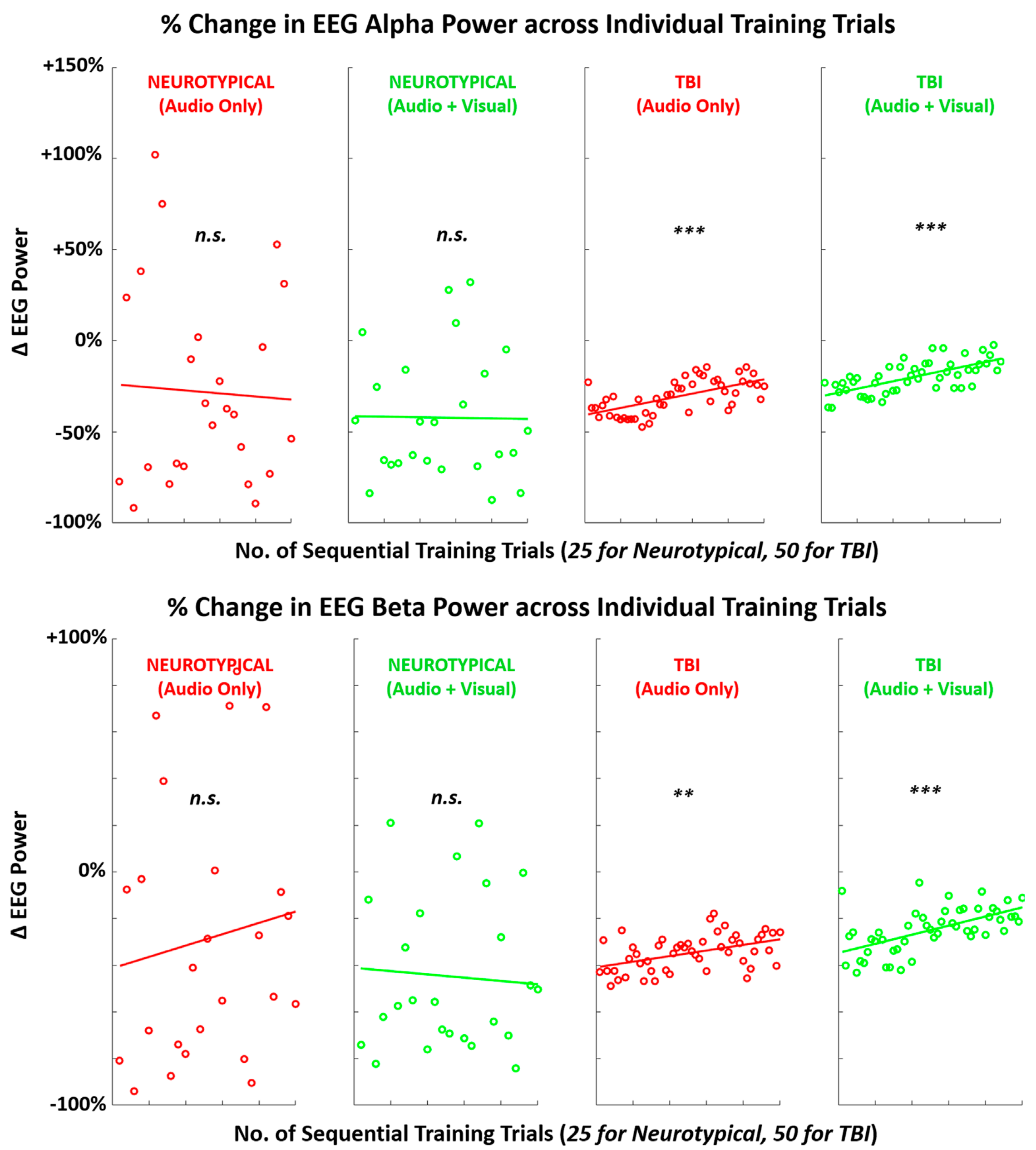

FIGURE 8
Mean (across participants) of EEG activity (alpha, beta) across sequence of training trials during training with augmented sensory feedback (audio or audio + visual) for each participant group (neurotypical or TBI). Linear regression fitted to indicate global trend within training block in each case pairing feedback condition and participant group. Note: p-values indicate non-zero value for slope coefficient (i.e., significant trend present) of linear regression; $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

and completion time; however, the additional visual cueing with multimodal feedback worsened performance in both metrics for neurotypicals. This seemingly paradoxical outcome across groups suggests a difference in how the added visual feedback is processed and leveraged for motor performance pending functional neurological states. In particular, multimodal feedback may support the expedited crossing of neural thresholds to improve learning as intended with multimodal feedback (Seitz and Dinse, 2007) for persons having TBI. Yet, for neurotypicals, the additional cueing may be excessive stimuli interpreted as confounding during task training and ultimately interferes with performance and learning progression (Spruit et al., 2016).

Such a finding suggests the need to optimize a computerized rehabilitation interface for users with neurological dysfunction. More specifically, guidance feedback may need to be delivered with greater sensory stimulation. The disturbed brain networks, such as after TBI, can alter how sensory feedback is processed for motor function (Nudo, 2013). Although not analyzed for significant differences, the brain plots in Figure 3 suggest the disparities in regional activation between TBI and neurotypical participants. Thus,

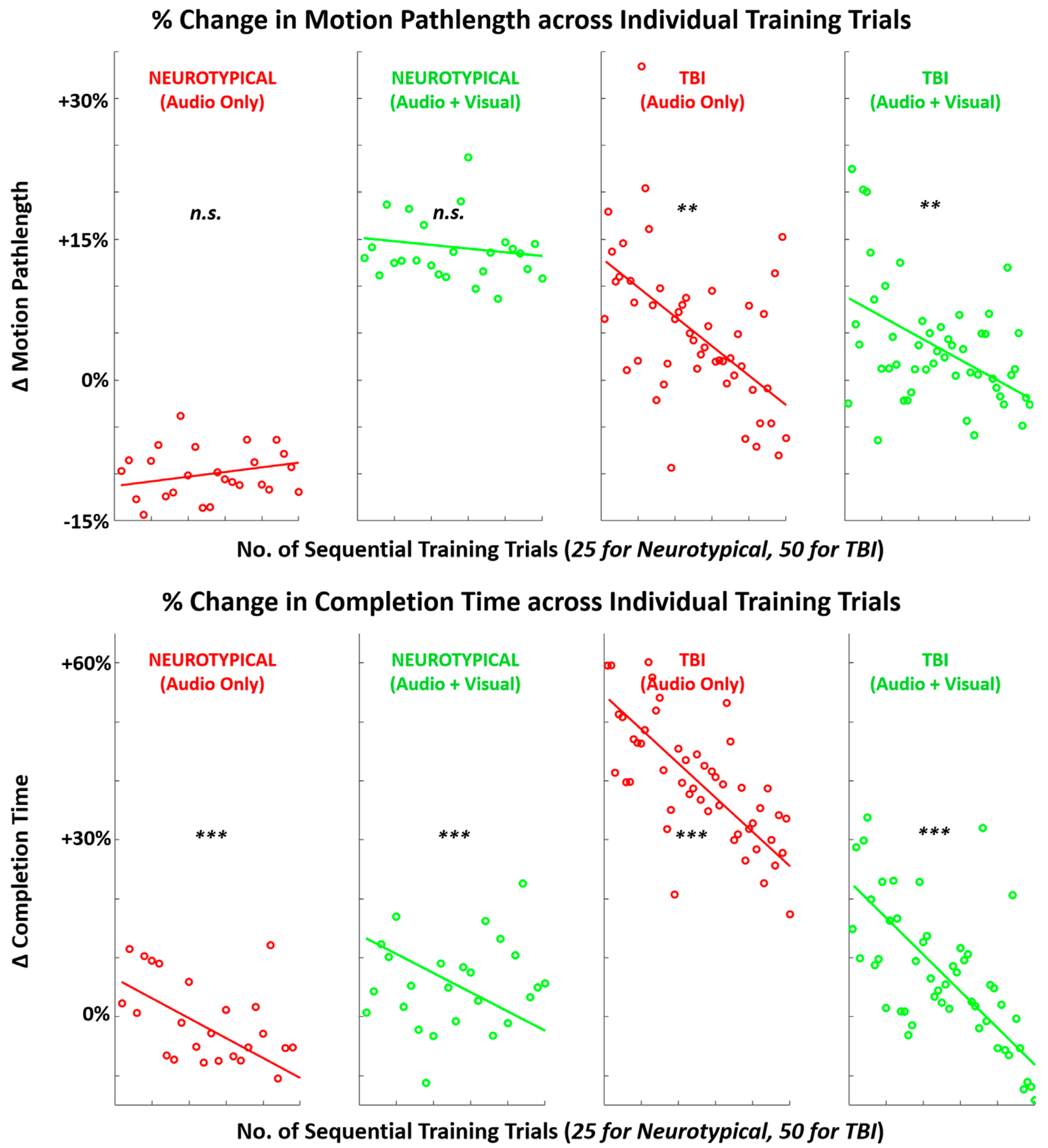

FIGURE 9
Mean (across participants) in performance metrics (motion pathlength, task completion time) across sequence of training trials with augmented sensory feedback (audio or audio + visual) for each participant group (neurotypical or TBI). Linear regression fitted to indicate global trend within training block in each case pairing feedback condition and participant group. Note: p-values indicate non-zero value for slope coefficient (i.e., significant trend present) of linear regression; $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

increasing sensory stimulation with guidance feedback, even if redundantly encoding the same performance information, may partially compensate for processing dysfunctions with TBI. In any case, assessing the responses to feedback by neurotypicals independently from TBI participants is warranted. However, we still conducted a 2-way ANOVA to determine if each measure is broadly affected by each of the two main factors of group and feedback condition. Only the EEG measures (i.e., alpha power, beta power, and EMG-EEG coherence) demonstrated significant factor-level effects and only for feedback conditions.

While alpha activity is typically suppressed with active movements, it can reflect greater motor preparation (Deiber et al., 2012) and be enhanced by motor training paradigms that increase cognitive flexibility (Lasaponara et al., 2017). The post-training increase in alpha-band activity may suggest the foundation for early and robust consolidation of motor learning features from a pre-learning state (Henz and Schöllhorn, 2016). This phenomenon is readily shown with differential learning, characterized by practice variability to facilitate faster learning rates (Tassignon et al., 2021). The grasp-and-place task for this study was repetitive as it did

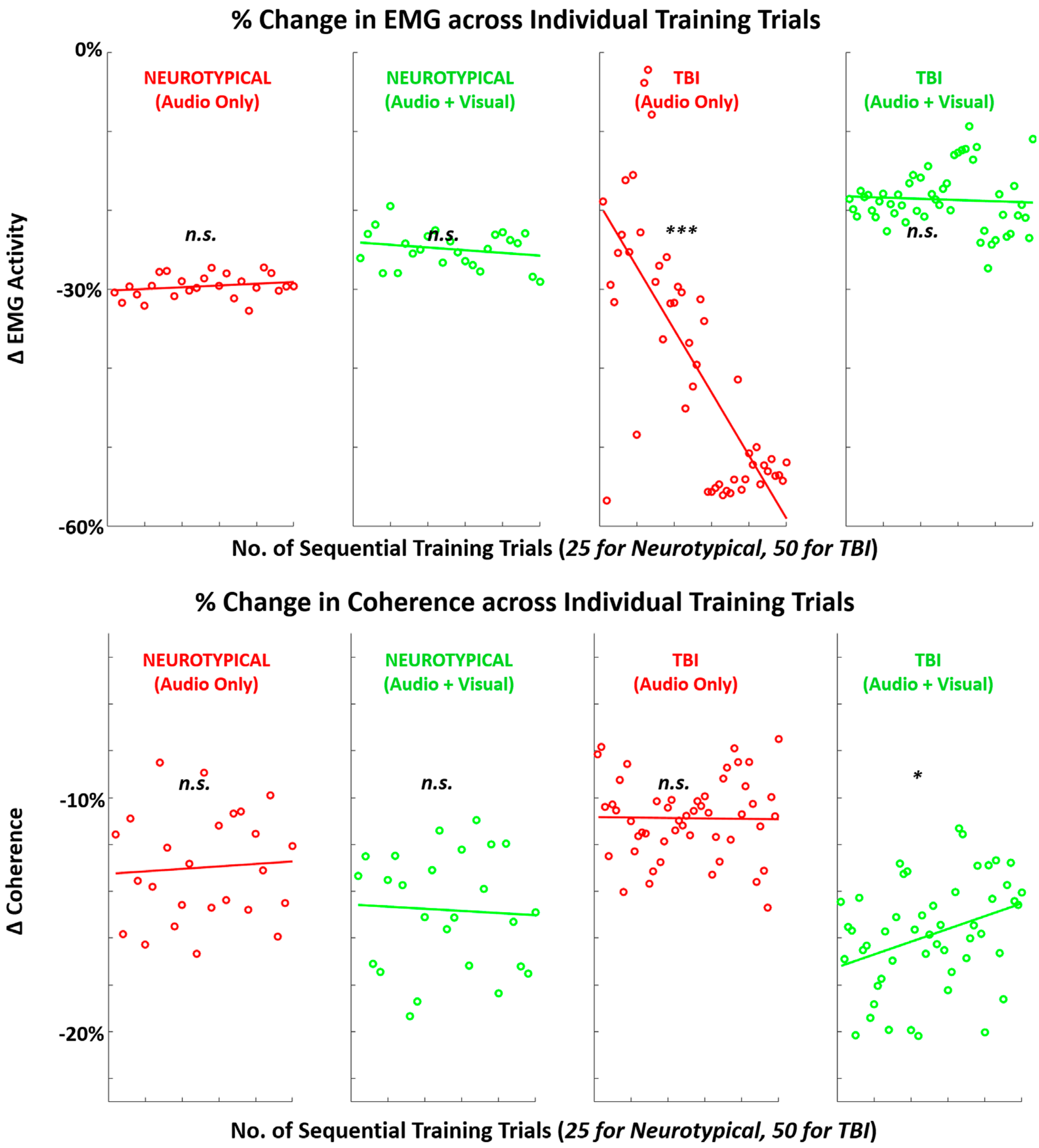

FIGURE 10
Mean (across participants) in EMG-related metrics (EMG amplitude, EMG-EEG coherence) across sequence of training trials with augmented sensory feedback (audio or audio + visual) for each participant group (neurotypical or TBI). Linear regression fitted to indicate global trend within training block in each case pairing feedback condition and participant group. Note: p-values indicate non-zero value for slope coefficient (i.e., significant trend present) of linear regression; $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

not vary between trials; however, participants may perceive more variability when training with multimodal feedback. In the case of TBI, this perception of variability may be more effectively leveraged to improve potential motor learning.

On the other hand, beta activity can indicate increased alertness, including by visual stimuli (Kamiński et al., 2012), as done in this study. Regarding motor function, beta waves, especially over the motor cortex, are associated with strengthened sensory feedback during movement changes (Lalo et al., 2007). Thus, the long-term implications of increasing beta activity after each training session may facilitate learning through higher sensory-guided attention during movement training. While EMG metrics in this study were relatively insensitive to changes in feedback training, EMG-EEG coherence was significantly reduced for neurotypicals when receiving multimodal feedback. Since corticomuscular drive, especially in the beta band, indicates a change in muscle coordination strategy (Reyes et al., 2017), the attenuation of corticomuscular coherence may suggest that neurotypicals experienced divided attention (Johnson et al., 2011) in perceiving the added visual cue.

TABLE 3 The mean slope value (percentage change per trial repetition) during training block per group-condition pair and *p*-values indicating non-zero slope.

Metric	NT-A	NT-AV	TBI-A	TBI-AV
EEG-alpha	−0.34 (p = 0.86)	−0.06 (p = 0.95)	**0.39 (p = 3.3E-06)**	**0.41 (p = 1.0E-06)**
EEG-beta	0.97 (p = 0.57)	−0.28 (p = 0.75)	**0.24 (p = 2.6E-03)**	**0.39 (p = 7.9E = 05)**
PERF-pathlength	0.10 (p = 0.14)	−0.08 (p = 0.47)	**−0.31 (p = 1.2E-03)**	**−0.22 (p = 4.2E-03)**
PERF-completion time	**−0.67 (p = 5.0E-04)**	**−0.65 (p = 3.0E-04)**	**−0.58 (p = 1.4E-07)**	**−0.62 (p = 3.1E-03)**
EMG-amplitude	0.04 (p = 0.28)	−0.07 (p = 0.30)	**−0.80 (p = 1.1E-07)**	−0.02 (p = 0.72)
EMG-M1 coherence	0.02 (p = 0.75)	−0.02 (p = 0.80)	−1.8E-03 (p = 0.93)	**0.05 (p = 0.032)**

Note: p-values < 0.05 are bolded.

Although assessing post-training effects across measures of EEG, performance, and EMG from the pre-training baseline was the primary objective of this study, we also examined trial-by-trial trends during training for each measure. This analysis provides insight into how these measures may be actively manipulated with each training condition before participants return to independent (unguided) task performance. Although both neurotypicals and TBI demonstrated increased post-training neurological activity, only TBI demonstrated a linear trend towards increased neurological activity within the training block. There was a significant non-zero slope towards increased power across sequential training trials in both the alpha and beta bands.

These findings indicate that TBI participants may have a more immediate tendency to reformulate neural connections during training with augmented feedback. Neural reorganization to facilitate motor recovery is a crucial objective with motor rehabilitation training, and it is primarily expected with visually guided actions (Kantak et al., 2012). Comparatively, neurotypicals may be more limited in their capacity for neural plasticity for a relatively simple motor task. Furthermore, these training trends in neural activation were mirrored with the key performance metric of motion pathlength for both groups. Only TBI participants exhibited a significant trend in reduced pathlength (better performance) during training with more trial repetitions. Such correlates between brain activity and performance can be expected during motor sequence learning (Orban et al., 2010). While the difference in the number of training trials for each group may have impacted the magnitude of the post-training effect, the same trends, i.e., progressive changes in metrics (Figures 8–10), for TBI are readily apparent even halfway through the block of training trials.

For the secondary performance metric of completion time, both groups demonstrated significant trends in reduction across training trials with both feedback conditions. This finding suggests that augmented sensory feedback naturally incentivizes faster movements with more training repetitions. This finding is consistent with another study demonstrating that augmented feedback can impact movement times of reaching movements, irrespective of fixed task parameters (e.g., movement amplitude) (de Grosbois et al., 2015). In comparison, training trends with EMG activity were not as evident. Still, TBI participants did demonstrate a significant training trend in reduced EMG with unimodal feedback and increased EMG-EEG coherence with multimodal feedback. Thus, only the TBI participants appeared to progressively re-organize neural and motor activity during single-session training with augmented sensory feedback.

Furthermore, this study revealed a positive linear-level dependence between higher alpha activity and improved motor performance for TBI, despite a relatively small sample size. This finding suggests that designing rehabilitation paradigms to target increases in alpha activity during the training of persons with TBI may support better motor performance. Identifying and understanding such correlations open new pathways to optimize computerized rehabilitation. For example, control systems can be developed to adapt (personalize) more intelligently specific VR design elements, including feedback features and enhancement levels (e.g., the brightness of color and pitch of sound). The objective of such control systems would be to modulate neural rhythms in ways that are more likely to induce targeted plasticity and increased gains in function.

A presumed limitation of this study is the lack of a more fundamental control condition whereby participants would undergo no augmented feedback for an entire training block. However, the primary goal of this work was to examine the differential impact of multimodal feedback within VR. Thus, this study's main limitation is that the scope of the evaluation is restricted to a single training session. Authentic learning, and gains in function, can only be ascertained with long-term assessments (e.g., tracking performance across multiple follow-up sessions). Furthermore, the margins of improvement with augmented training feedback we observed in the single session, although significant, likely would not produce a discernible change in performing activities of daily living. Still, short-term performance improvements (i.e., immediately after a single training session) can indicate this approach's potential for motor learning (Reyes et al., 2017). Initially developed in (Liu et al., 2021), our training approach integrates the sense of agency with augmented sensory feedback cues. Since alpha power may be the primary neural oscillation in the sense of agency (Kang et al., 2015), our approach may leverage a cognitive-sensorimotor synergy in motor training. Furthermore, alpha activity at human M1 for task-specific involvement indicates the potential for rapid motor learning (Muellbacher et al., 2001). Thus, increased alpha activity and improved performance for the TBI group suggest the potency of multimodal VR feedback to promote neuroplasticity for more effective neuromotor rehabilitation.

5 Conclusion

This study demonstrates that training with agency-inspired augmented feedback in VR can significantly impact post-training neural activity, motor performance, and muscular engagement, depending on if the feedback is unimodal or multimodal. Furthermore, these effects can also depend on whether the person has a cognitive impairment (e.g., traumatic brain injury). A notably higher increase in alpha- and beta-band EEG activity after training, especially in brain regions associated with motor planning and execution, may offer an underlying neural explanation for improving motor performance. Thus, augmented feedback, particularly multimodal feedback, provided with VR is a promising approach for rehabilitating motor function after brain injury. Results from this study should motivate future investigations into optimizing the delivery of sensory-driven feedback from computerized rehabilitation interfaces aiming to maximize functional outcomes.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Stevens IRB and the Kessler Foundation IRB. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in these studies.

Author contributions

ML wrote the first draft and is primarily accountable for accuracy and integrity of data SW was the primary developer of the mixed-mode reality platform SW, SoS, and RN (lead) contributed to conception of study ML, SoS, and RN (lead) contributed to design of study ML (lead), SeS, MG, SoS, and RN contributed to execution of study ML (lead), SeS, MG, and SD contributed to data collections ML and RN contributed equally to statistical and data analysis ML and RN (lead) interpreted data and revised the manuscript All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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How should robots exercise with people? Robot-mediated exergames win with music, social analogues, and gameplay clarity

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Introduction: The modern worldwide trend toward sedentary behavior comes with significant health risks. An accompanying wave of health technologies has tried to encourage physical activity, but these approaches often yield limited use and retention. Due to their unique ability to serve as both a health-promoting technology and a social peer, we propose robots as a game-changing solution for encouraging physical activity.

Methods: This article analyzes the eight exergames we previously created for the Rethink Baxter Research Robot in terms of four key components that are grounded in the video-game literature: repetition, pattern matching, music, and social design. We use these four game facets to assess gameplay data from 40 adult users who each experienced the games in balanced random order.

Results: In agreement with prior research, our results show that relevant musical cultural references, recognizable social analogues, and gameplay clarity are good strategies for taking an otherwise highly repetitive physical activity and making it engaging and popular among users.

Discussion: Others who study socially assistive robots and rehabilitation robotics can benefit from this work by considering the presented design attributes to generate future hypotheses and by using our eight open-source games to pursue follow-up work on social-physical exercise with robots.

KEYWORDS

human-robot interaction (HRI), socially assistive robotics (SAR), physical HRI, exercise games, personal robots, rehabilitation robotics

1 Introduction

The worldwide population is becoming less physically fit over time. For example, in the United States, 80% of adolescents and adults are insufficiently active (Piercy et al., 2018). This inactivity is accompanied by a reduction of metabolic health, an increase in cardiovascular morbidity and mortality, and an increase in the probability of diseases such as adolescent obesity, type 2 diabetes, and certain cancers (Must and Tybor, 2005; Young et al., 2016; de Rezende et al., 2014). On the other hand, physical activity as simple as standing up, walking, or taking exercise breaks comes with significant health benefits, such as lowering mean arterial blood pressure (Mainsbridge et al., 2014) and lowering insulin and glucose levels after meals (Dunstan et al., 2012; Bailey et al., 2016; Yates et al., 2020). Many technologies have previously been introduced to encourage people to be more active, from wearable devices (Kerner and Goodyear, 2017; Giddens et al., 2017) to phone or computer applications that support break-taking (op den Akker et al., 2014; Cooley and Pedersen, 2013); however, the prompts they deliver are often ignored, and even successful past studies of activity-promoting applications and devices show limited use and retention (Cooley and Pedersen, 2013). Compared to non-social or software-based encouragement approaches, social robots that are physically embodied are more likely to be able to encourage physical activity (Bainbridge et al., 2011); (Schneider and Kummert, 2018). These socially assistive robots have been evaluated as motivation companions for a variety of age groups, ranging from children (Swift-Spong et al., 2016; Guneysu and Arnrich, 2017; Akalin et al., 2019) to older adults (Fasola and Matarić, 2012; Avioz-Sarig et al., 2021).

Related work has begun to consider ways to use robots to promote exercise, testing a range of approaches from activities involving wearable robotic exoskeletons (Ren et al., 2012; Riener et al., 2011) or physical interaction with robot end-effectors Rodgers et al. (2019) to social interactions with an encouraging robot (Fasola and Matarić, 2012; Kashi and Levy-Tzedek, 2018) or a musical robot (Baur et al., 2018). Findings to date show that adults of widely varying age all prefer exercise games (exergames) with a physically embodied robot over exercise with onscreen video of a robot (Eizicovits et al., 2018; Feingold-Polak et al., 2018). Past work in this space has typically employed either social interaction or physical interaction to support the needs of users, but seldom have robotic systems incorporated both. As pictured in Figure 1, the eight games analyzed in this article include six games that are socially and physically interactive in an intentional, dynamic, and high-energy way, thus following best practices for exergaming such as the dual flow model of mental and physical experience (Sinclair et al., 2009). Our past quantitative results demonstrated that these six social-physical games were generally more pleasant, enjoyable, engaging, cognitively challenging, and energy-inducing than the two studied games that lack physical interaction (Fitter et al., 2020). At the same time, not all of the physically interactive games were successful at inducing a positive exercise experience. This follow-up paper uses inductive analysis to dig further into the experience surrounding these exercise games and better understand why the most preferred games won user favor.

In the work presented here, our key research question is: *what attributes make robot-mediated exercise games successful at inducing a positive exercise experience?* We consider related literature on video games and assistive robotics in Section 2 to help identify potentially relevant game components. Section 3 describes our eight exercise games and their key components, in addition to the methods used to collect human experience information for each exergame. We move from the hypothesis-driven approach of our relevant past paper Fitter et al. (2020) to a more open-ended and hypothesis-generating inductive approach (centered on thematic analysis of qualitative data not considered in the past paper, with framing and context from the previously presented data) to better illuminate the path forward in human-robot exercise game interactions. The inductive analysis results in Section 4 include three main resultant themes: musical cultural touchstones, social experience, and gameplay clarity. We examine these results from the perspective of improving human-robot exercise gameplay for broader robotic systems and use cases promoting physical activity. Section 5 discusses what these results mean for human-robot exercise generally, with a particular emphasis on exploring cultural and social design elements and clear gameplay design. Key contributions of this work center on the identification of factors that can be leveraged in design and studied in future empirical studies to improve human-robot exergames.

2 Background

We draw essential context for the present work from related research on exercise games in rehabilitation robotics, design principles in video games as they relate to rehabilitation, and assistive robots.

Study of exergames involving robots and other technologies extends more than 30 years into the past. Early multimedia technologies for exergaming appeared in the video-gaming space, where activities from the 1987 *World Class Track Meet* for the Nintendo Entertainment System to the modern-day *Ring Fit Adventure* for the Nintendo Switch (and many games in between) have introduced ways for players to be physically active while gaming (Bogost, 2005; Nintendo, 2019). In addition to their presence in the consumer gaming space, exergames are a popular approach for encouraging general physical activity, promoting persistence, and providing entertainment in physical therapy. In the broad realm of physical activity, past work has focused on methods for evaluating behavior change (Abraham and Michie, 2008; Kok et al., 2016), which we could potentially use in future stages of this work. Other general physical activity research shows that planning routines together with users, providing instruction in physical activity, and reinforcing user effort are effective ways to increase human self-efficacy feelings toward exercise (Williams and French, 2011). In the rehabilitation space, particularly for arm exercises after stroke, researchers have proposed a multitude of exergames that involve peripherals ranging from handheld objects and joysticks (Goršič et al., 2017; Pereira et al., 2019) to robot arms and small mobile robots (Eizicovits et al., 2018; Rodgers et al., 2019; Guneysu Ozgur et al., 2018). Evidence to date shows that exergames that involve both social and physical interactions are likely to be most successful (Fasola and Matarić, 2012; Kashi and Levy-Tzedek, 2018). Accordingly, a fundamental idea in the design of our exercise games was the merging of these two types of interaction.

To design exergames that engage the user, we needed to consider and understand the extensive literature on games and gameplay. In gaming at large, a key challenge is designing activities that are both attractive and effective (Abeele et al., 2020). Vahlo and Hamari (2019) suggest that the five reasons why users choose to play video games are immersion, relatedness, fun, competence, and autonomy. For the topic of immersion in particular, Garone et al. (2020) emphasize the importance of touch and auditory stimuli. This observation aligns with our proposed use of social-physical contact and some of the game-design principles discussed in Section 3. Incorporating best-practice game-design ideas into exergames is crucial; these games need to be well-designed to overcome the monotony of the repetitive therapeutic exercises underlying

FIGURE 1
Illustrative frames of users playing the eight studied exercise games. Further details about each game appear in Section 3 and Fitter et al. (2020).

most such activities. In exergame design, Luckner et al. (2018) further suggest incorporating components such as goal setting, avoiding competition, avoiding punishment, showing progress, and embedding exercises in daily routines to increase engagement. Active video games can promote different types of enjoyable energy expenditure (Lyons et al., 2011). In this past research, although energy expenditure was highest in fitness and dance games, enjoyment was highest in band simulation games that used licensed popular songs. This finding agrees with foundational research on conventional games that highlights the value of familiarity in making games appealing (DeKoven, 2013). Furthermore, the video-gaming literature highlights six forms of playfulness that roboticists could also seek to evoke: embodied investigation, constructive investigation, investigative storytelling, constructive storytelling, embodied storytelling, and embodied construction (Legaard, 2020). Another motivating factor in video games is the aspect of challenge, which can be broken into four components: physical, analytical, socioemotional, and insight (Vahlo and Karhulahti, 2020). These elements of playfulness and challenge informed our design and understanding of the investigated robot exergames. We return to key gaming ideas as framing in Section 3.2 as we introduce different exercise game components from our own work.

Our approach to encouraging exercise is also guided by past work that has leveraged social physically embodied robots as a unique way to motivate people. Socially assistive robotics Feil-Seifer and Matarić (2005) has shown potential for motivating and engaging people in a variety of tasks such as tutoring, physical therapy, and practicing the activities of daily living. One notable example used dance-based rehabilitation robotics for adults with Parkinson's disease (Allen et al., 2017). This dance therapy with a robotic partner yielded improvements in gait, balance, and disease symptoms after 3 weeks of adapted tango classes. Exercise-based socially assistive robotics work showed that both patients and clinicians positively perceive robots used in conjunction with a treadmill for cardiac rehabilitation (Casas et al., 2019) and that a sociable robot to promote physical exercise is preferred over a more pragmatic and task-oriented system (Fasola and Matarić, 2012). Examples of socially assistive robots for exercise further include robots for walking practice promotion (Hamada et al., 2016; Mucchiani et al., 2017) and exercise activity teaching (Matsusaka et al., 2009; Moreno et al., 2016; Avelino et al., 2018). The humanoid robot NAO has been extensively used as a buddy that plays exergames with patients, such as imitation games for children (Pulido et al., 2019; Guneysu and Arnrich, 2017) and memory games for stroke rehabilitation (Sanchez et al., 2019). The Pepper robot has also been used an exercise buddy for post-stroke rehabilitation (Feingold-Polak et al., 2021) and as an autonomous empathetic exercise robot (Shao et al., 2019; Carros et al., 2020; Martinez-Martin and Cazorla, 2019; Cobo Hurtado et al., 2021; Akalin et al., 2019). In general, across user groups, imitation games appear to be the most common form of exergame performed by socially assistive robots (Pulido et al., 2019; Guneysu and Arnrich, 2017; Shao et al., 2019; Bäck et al., 2013; Görer et al., 2013; Matsusaka et al., 2009; Lewis et al., 2016). Our exergames with Baxter attempt to introduce a broader range of interaction types for robotic exercise-promotion systems. We also introduce new aspects to the interaction, such as a robot with a large workspace, dynamic robot motion capable of challenging a broader range of users, and direct social touch between the robot and the user.

3 Methods

3.1 Exercise games

As pictured in Figure 1 and described more thoroughly by Fitter et al. (2020), we developed eight exercise games that a user can play with a Rethink Robotics Baxter Research Robot [a human-sized upper-body humanoid robot with a face screen and built-in joint compliance (Rethink Robotics, 2012)]: the Strength, Agility, Mimic, Roboga, Handclap, Teach, Stretch, and Flamenco games. We were inspired by past work in robotic entertainment (e.g., Nuñez et al., 2014) to incorporate robot facial expressions, robot nonverbal behaviors, music, and audiovisual feedback into the games. The employed robot facial expressions come from Fitter and Kuchenbecker (2016)'s validated open-source Baxter face database, and the robot wears boxing pads on its end-effectors to facilitate safe contact. With feedback from experts in game design, rehabilitation robotics, physical therapy, and occupational therapy, these games were designed to promote moderate upper-limb activity and cognitive exercise. Brief descriptions of the games from Fitter et al. (2020) follow in descending order of user popularity, as reported later in this article:

- The Strength game is a boxing-training-like interaction during which Baxter holds up its end-effectors centrally and prompts the user to contact them.
- The Agility game challenges users to wake a "sleeping" Baxter by making rapid contact with its end-effectors.
- The Mimic game is a memory game during which the user teaches Baxter an increasingly long pattern of left-, right-, and both-handed claps.
- The Roboga game (an abbreviated spelling of "Robot Yoga") requires the user to hold their arms aloft in poses demonstrated by Baxter.
- In the Handclap game, Baxter teaches the user a sequence of hand-clapping game motions by demonstrating the motions and then playing the game with the user.
- In the Teach game, the user can move Baxter's arms to different positions to play and record musical chords mapped to its workspace.
- In the Stretch game, Baxter holds its end-effectors out wide, and the user must copy its pose and hit both of its end-effectors in each new pose.
- In the Flamenco game, Baxter teaches the user a sequence of dance moves to music, and the user then replicates the dance along with the same music clip.

To support additional understanding of the games, further explanation and demonstration of each activity is available in the Supplementary Video S1 included with this manuscript. We provide more discussion of key game elements matched to the video-game literature in the following subsection.

3.2 Exercise game components

From the perspective of common video-game (and exergame) mechanics, we had four components in mind while designing the games. These ideas are common in the related literature, although the perceived value of each component often does not match across the video-game and exergame contexts. Here, we explain how each component is connected to a subset of the games, and we return to these categorization ideas when discussing the inductive analysis later in this paper. The four identified components are: repetition, pattern matching, music, and social design.

3.2.1 Repetition

Interestingly, though repetition is viewed negatively in the video-game literature (Desurvire and Wiberg, 2009), this element is essential in rehabilitation (Langhorne et al., 2011; Stevens and Tan, 2014; Bütefisch et al., 1995). This difference is one of the ways the investigated exercise games are different from games more generally; gameplay needs to be reevaluated as it moves from screen-based to embodied in the physical world, and as the goal shifts from pure entertainment to improving health. In accordance with the common rehabilitation need, four of the exercise games had an extremely repetitive premise (i.e., the robot struck a pose, and the human user matched the pose and possibly made contact with the robot's end-effectors), as further described below. One of the main aspects that varied across these games was the workspace size; the order below reflects largest to smallest workspace used.

- Roboga: very large workspace; the robot struck four possible poses with fully extended arms, and the user matched the poses without contact
- Stretch: large workspace with a high number of possible robot poses (the result of mapping Baxter's workspace into abstract musical quadrants), after each of which the user contacted the robot
- Strength: medium workspace with six possible robot poses (similar to boxing training), after each of which the user contacted the robot
- Agility: small workspace with just one central robot hand pose (the robot did not move at all, other than in passive response to the user's hand contacts), which the user contacted repeatedly

The cycles of hand contact in these premises made them convenient for games designed with physical intervention in mind. The varying workspace could help to increase (or decrease) the level of spatial awareness required for the game, as needed for particular users or user populations.

Although the workspace and number of poses varied across these games, the mechanics of the portion of the game with active human input was very similar in premise, especially for the Stretch and Strength games. However, as discussed more in Section 4, user perceptions of these games varied widely.

3.2.2 Pattern matching

Compared to the repetitive games above, these games built up to larger patterns of movement, as demonstrated by either the human user or the robot. This type of pattern matching is common in video games [e.g., in party games, minigames within popular franchises, and many games discussed in Lyons et al. (2011)] and rehabilitation (e.g., the socially assistive imitation games mentioned previously). The games in this category are listed in alphabetical order.

- Flamenco: robot lead, with no physical contact with the user. The robot demonstrated a sequence of three dance moves (out of four possible moves: a flourish or a clap to the left or right side) that the user then had to replicate. The pattern of dance moves grew by one move with each repetition and continued in this way until the game ended.
- Handclap: robot lead, beginning with a pattern of three handclaps (out of five possible moves: a clap across the body or on the same side with the left or right hand, or a two-handed contact) taught by the robot and then completed by the user and robot together twice. The game then lengthened by one handclap in each round, until the user made it to the fixed end of the game or lost the game by missing consecutive claps.
- Mimic: human lead and involving physical contact with the robot. The game began with a pattern of one move (out of three possible moves: left, right, or two-handed contacts) and built up a longer pattern until a mistake occurred.

The building patterns in these games, which the user needed to remember and replicate, linked them well to potential interventions that require cognitive effort, in addition to the physical requirements implicit in dancing or making contact with the robot.

3.2.3 Music

Music games involved an element of music-making or a musical background theme as context. As with pattern matching, musical themes are common in both video games and rehabilitation. The work of Lyons et al. highlights popular musical games such as Rock Band and Dance Dance Revolution (Lyons et al., 2011), and we found several musical activities among the surveyed rehabilitation systems (e.g., Chen et al., 2017; Baur et al., 2018). The following list of these games appears in order from strongest/most ingrained to weakest musical premise.

- Teach: focused on music composition with the robot as an input device. The shoulder angle of each robot arm corresponded to one note in an abstract musical space, which the user could hear by turning the corresponding robot wrist. The user could lock in two-note chords to add to their composition by turning both of the robot's wrists simultaneously. At the end of the song, the full composition played back along with the corresponding robot arm poses.
- Strength: this boxing-style interaction involved the theme music from the movie *Rocky* as a background soundtrack.
- Flamenco: this dance interaction occurred to the song "Malagueña."
- Stretch: a musical chord played after each successful hand contact was registered, and playback at the end of the game shared the whole song while the robot held still, with playful incorrect notes for any poses that the user missed during the game.
- Mimic: three different drum beats played to correspond to (and register the success of) each demonstrated clap type (left hand, right hand, or both hands).

3.2.4 Social design

Social interaction is a major element in both video games and rehabilitation. For example, in the Bartle taxonomy of video-game player types, "socializer" is one of the four major categorizations (Bartle, 1996), and socially assistive robotics is a full and burgeoning field in rehabilitation (Feil-Seifer and Matarić, 2005). Accordingly, seven of our eight games included interaction elements that were meant to make the activity social in some way. This type of design was central to all games aside from Teach, which was designed with the idea of the robot as a pure input device. The list of social games below appears in alphabetical order.

- Agility: the social analogue for this game was waking up a stubborn sleeping person. The robot snored and displayed a sleeping face at the start of the game. The snoring sound continued until the robot "woke up" (i.e., upon successful game completion). Baxter's face changed from cool to warm colors in five discrete steps as the robot transitioned from a sleeping state to an awake state. The displayed robot face opened and closed the mouth to simulate snoring. As the participant made more contacts with the robot's hands, the robot occasionally blinked, as if awakening briefly. If the participant paused for a sufficient duration, the robot went back to sleep. At the end of the game, if the participant succeeded, the robot stretched and yawned and the robot's expression changed to one of joy.
- Flamenco: the social analogue for this game was dancing together with a dance partner. Baxter's face color was yellow when it demonstrated the sequence and changed to purple when it waited for the participant, its partner, to replicate the sequence. The robot displayed a smiling expression on its screen throughout the interaction.
- Handclap: the social analogue for this game was playing childhood hand-clapping games with a friend, an activity which often transfers over to team-building or icebreaker activities. Baxter indicated that it was ready to clap hands with the participant by changing its face color from yellow to purple after demonstrating the sequence of hand-clapping motions. Baxter maintained a happy expression as long as the participant was physically interacting with its end-effectors. However, if the participant missed more than three moves, Baxter's face

displayed a sad emotion and the arms slumped in a dejected pose.

- Mimic: the social analogue for this game was playing pattern-building games with a peer, either with one another or with a toy like the pattern-matching game "Simon" (Wikipedia, 1978). Baxter changed its face color to green and nodded to indicate that it was waiting for the human user's pattern. Baxter smiled and played a sound corresponding to each detected move during the participant's teaching segments. Baxter's face color changed to purple when it was replaying the learned moves together with the user. If Baxter lost a game, it performed a playful shrugging motion. In cases when the participant lost the game, Baxter raised its arms in joy and displayed a playfully impolite face with a tongue sticking out.
- Roboga: the social analogue for this game is doing yoga with an exercise partner. This game's slow-paced stretching challenges the user to keep their limbs aloft, and Baxter's presence functions similarly to a calm exercise partner. Baxter's face changed from cool to hot colors to visualize the duration to hold each pose. The robot displayed a smiling expression on its screen throughout the interaction.
- Strength: the social analogue for this game was practicing boxing with a peer or coach. The robot moved its hands to a specific pose, changed the face color from blue to green, and played a bell sound to indicate it was ready for the participant to perform the boxing action. During the game, different levels of Baxter facial expression happiness (i.e., joyous, happy, neutral, sad) gave a running indicator of the user's performance level, with the facial expression changing whenever a change in performance tier occurred. If the robot reached the sad face, the music also stopped, although the participant could still resume hand contacts to catch up and successfully finish the game. At the end of the game, the robot struck a pose whose level of celebration indicated the user's game performance.
- Stretch: the social analogue for this game was a hand-tag or keep-away interaction during which a taller person (in this case, Baxter, which is tall relative to the average user) tries to playfully evade someone else and challenge them to reach far up and around. When a successful contact was detected, Baxter displayed a big smile and moved to the next pose. At the end during the song replay, Baxter displayed a smile with a purple face for all the successful contacts and a playful smirk with a red face for any failed contacts.

In addition to the above behaviors, Baxter randomly blinked its eyes during the entire study. When idle, the robot also randomly rotated its head left and right to create the illusion of observing its surroundings.

3.3 Exploratory study methods

We previously conducted an exploratory study to evaluate how users respond to exercise games with Baxter and how such games may fit into assistive applications. Eligible participants played a short segment of each game, immediately reported their perceptions of that game, and selected their favorite game to try again in a final longer free-play interaction. The University of Pennsylvania (Penn) IRB approved all study procedures under protocol 826370. The key research question guiding the inductive analysis approach presented in this paper asks how attributes that guided the exergame designs (i.e., repetition, pattern matching, music, and social design) and key themes observed during the study may connect to game success at inducing a positive exercise experience.

3.3.1 Study factors

This experiment employed a within-subjects design that enabled all participants to experience all eight exercise games pictured in Figure 1. The experimenter read scripted instructions to each participant to prepare them for each semi-randomly ordered game interaction. When referring to each game, the experimenter used only a letter label (A-H), rather than the game name, to avoid unduly influencing participants' interaction styles.

3.3.2 Participants

We recruited participants using flyers in the Philadelphia area and emails to university listservs. Thirty-nine participants (20 male and 19 female) enrolled, gave informed consent, and successfully completed the study. One additional male participant completed only part of the study, as further explained in Fitter et al. (2020); we include data collected before his withdrawal and therefore have none of his demographic responses. During one participant's session, we failed to record video of the first exercise game. Thus, for the video coding analyses later, the number of reported participants per game ranges from 38 to 40.

Participant ages ranged from 18 to 70 years old (aged 41.1 ± 18.7), where our notation represents the mean ± the standard deviation. 28 participants were affiliated with Penn. According to the demographic survey responses, the user group was made up of 21 individuals from science, technology, engineering, or mathematics (STEM) fields and 18 from non-STEM fields. On a scale from 0 to 100, participants ranked their experience with robots as 34.2 ± 30.0 and with Baxter as 21.2 ± 20.0. All participants possessed full function in their arms and hands and had normal or corrected-to-normal vision and hearing.

3.3.3 Measurement

As detailed more thoroughly in Fitter et al. (2020), we recorded data about participant physical and cognitive state at the start of the study using the Box and Blocks manual dexterity assessment (BnB) (Mathiowetz et al., 1985), Beck's Depression Inventory (BDI) (Beck, 1979), and (for older adults) the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). We also recorded user height. Small adjustments were made to the gameplay based on each individual user's arm span, motion speed capabilities (from the BnB performance), and cognitive function (from the MoCA score). Participant performance on these opening tasks was as follows: BnB scores of 60.1 ± 8.4 blocks moved per minute, BDI scores of 4.1 ± 5.3 where scores above 16 indicate depression (which could affect participant motivation), and older participant MoCA scores of 26.3 ± 2.6, where scores below 26 indicate mild cognitive impairment or dementia.

We also administered four further surveys during the study:

- An opening survey about pre-conceived notions of the Baxter robot based on a Unified Theory of Acceptance and Use of

Technology (UTAUT)-centered questionnaire from Weiss et al. (2008) and additional questions from Heerink et al. (2009).
- A game evaluation survey after each game experience based on the Self-Assessment Manikin (Bradley and Lang, 1994), the NASA Task Load Index (TLX) (Hart and Staveland, 1988), enjoyment and engagement questions from past robotics work (Heerink et al., 2008), exercise level from the Borg perceived exertion scale (Heath, 1998), pain level from the Wong-Baker FACES pain rating scale (Garra et al., 2010), and a custom safety question from our own past work (Fitter and Kuchenbecker, 2018).
- A closing evaluation with the same robot evaluation questions plus general free-response questions.
- A demographic questionnaire.

Each of the self-rating questions was administered on paper using a continuous scale from 0 to 100. We verbally asked participants to select their favorite game after experiencing all exergames. We also videotaped the study and recorded data from Baxter's sensors. The detailed results of the continuous-scale survey questions are not covered in this article since they were already analyzed in depth (Fitter et al., 2020).

3.3.4 Study procedure

Each person came to the lab for a single 90-min session. Before the study interactions began, the participant completed the screening activities mentioned previously. The user received background information on Baxter and completed an opening survey. Next, the participant stood facing Baxter and played samples of the eight different exercise games in a semi-random order counterbalanced across participants. After each exergame, the user completed a survey about that game. The relayed instructions for each game and the general gameplay concept for each game are further explained in a video available as part of this article's Supplementary Materials, and the source code for these exercise games is available at Fitter (2020). After the eight games, the user refreshed their memory of the game options by watching video snippets of all the games (in the same order as they had experienced the games), selected their favorite game, and entered a free-play mode during which they could play that game for up to 10 min. Lastly, participants completed a closing survey and a brief demographic survey. Participants received $20 for completing the study and up to $10 for transportation to and from the study site.

3.3.5 Past analysis and results

As further reported in Fitter et al. (2020), our past work used analysis of variance tests on the questionnaire data to discover that games combining social and physical interaction were most pleasant, enjoyable, engaging, cognitively challenging, and high energy. Participant trust and confidence in the robot increased over the course of the study. There were also key differences in experience across age and gender; older adults experienced more exercise, energy, and engagement, and female users were more accepting of the robot than male users were.

3.3.6 Current analysis

This article's analysis focuses mainly on video coding, free-response data, and study video transcripts, as detailed below. As part of our early data analysis, we performed a *video-coding process* in which a trained annotator developed a codebook with the help of the research team. The videos were coded using MAXQDA 2018 (VERBI Software, 2018). The video annotation codes were designed to identify user verbalization and gestures that the robot could not automatically detect. The audio transcripts included three categories: comments made about the robot's appearance or behavior, comments made about gameplay, and user verbalization to the robot. Items from the codebook for the videos and the audio transcripts appear in Supplementary Appendix SA and include general outcomes such as the number of times each participant attempted each game as well as game-specific events such as winning or making a particular mistake. All study videos were coded by the trained annotator, and a second trained rater evaluated a subset of the codes for which the primary annotator was unsure of their annotations. Any consistent coding differences were handled by discussion with the full research team.

To better understand the higher-level implications of these data streams taken together, we next used an *inductive approach to thematic analysis* (Maxwell, 2012; Creswell and Poth, 2016), following an iterative approach to discover patterns within the data and capture the qualitative richness of the phenomenon (Fereday and Muir-Cochrane, 2006). We performed iterative thematic labeling of all the text data (i.e., answers to free-response survey questions and transcripts of game-relevant participant speech during sessions) with labels related to the focus of each text snippet and the emotion of each text snippet. We then incorporated individual participant demographics, further codes from the video-coding process, and groupings of labels by game to discover patterns and cluster our labels into the themes presented in this work. A first research team member performed the initial thematic analysis, and a second team member reviewed the work and asked clarifying questions as needed until both parties agreed upon the proposed result. Any consistent questions or labeling differences were again discussed with the full research team. We also note favorite game selections of participants and self-reported exercise levels in the current manuscript as important context, but the main purpose of this follow-up work is to inform and generate future hypotheses.

4 Results

To build on our past findings and move toward a more holistic understanding of types of exergames, we present results from inductive analysis of both written and verbal user reactions to the exercise games. Parts of these analyses draw on the video coding to elucidate similar observations in a different way.

The breakdown of the participants' favorite game helps to frame part of what is interesting about the results. The following list relays the frequency of each game's selection as a participant's favorite, in addition to a reminder of key game components discussed previously.

- Strength: 18 selections; repetitive game, musical design, social design
- Agility: 6 selections; repetitive game, social design
- Mimic: 5 selections; pattern-matching game, musical design, social design

- Roboga: 4 selections; repetitive game, social design
- Stretch: 2 selections; repetitive game, musical design, social design
- Handclap: 2 selections; pattern-matching game, social design
- Teach: 2 selections; musical design
- Flamenco: 0 selections; pattern-matching game, musical design, social design

Further, the games are intended to be exercise games, so it is important to consider their success in eliciting exercise alongside other factors. Accordingly, as previously reported in Fitter et al. (2020), the mean and standard deviation of the self-reported exercise levels (reported as $M \pm$ SD, with a maximum score of 100) for each game appear below, in order from most to least exercise elicited.

- Agility: exercise level of 54 ± 23
- Strength: exercise level of 39 ± 25
- Roboga: exercise level of 36 ± 23
- Handclap: exercise level of 27 ± 22
- Stretch: exercise level of 27 ± 21
- Flamenco: exercise level of 24 ± 21
- Teach: exercise level of 24 ± 22
- Mimic: exercise level of 21 ± 18

The participants in the study spanned wide ranges in age, cultural background, professional background, technical training, physical ability, and cognitive ability. Participant feedback reflected this heterogeneity; however, three common topics in particular emerged throughout the thematic analysis process, as detailed in the following subsections.

4.1 Musical cultural touchstones

The first of the identified themes, musical cultural touchstones, may be part of the story behind why games with similar repetitive premises could be perceived so differently. Based on the sorted qualitative feedback, the use of familiar music appears to be one main reason for the Strength game's great popularity. Looking across musical games, the main category to which this theme applied, we see cases of implementation success, implementation failure, explicit missed opportunities, and implicit missed opportunities:

- Musical cultural touchstones done well: Strength
- Musical cultural touchstones done wrong: Flamenco
- Explicit missed opportunities: Stretch, Teach
- Implicit missed opportunities: Mimic

Games with musical touchstone comments tended to be the same as activities that led to spontaneous comments on the game generally, which we captured in the experiment video annotations. As shown in Figure 2, there were no verbal mid-activity game comments for any of the non-musical games (i.e., Agility, Handclap, and Roboga), musical games (specifically, Strength, Stretch, Teach, and Flamenco) collectively led to all 14 mid-play game-focused comments. Below we consider these notes alongside written free-response feedback provided by participants, with an emphasis on comments that focused on the musical element.

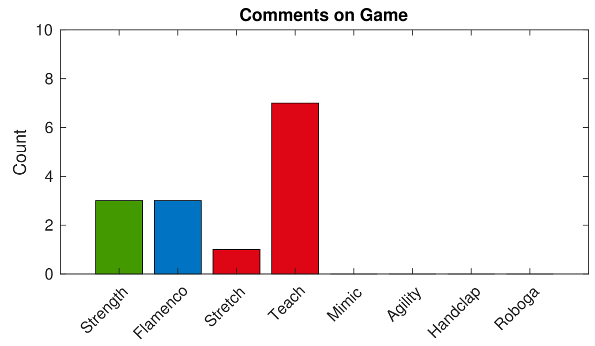

FIGURE 2
Number of verbal gameplay comments that occurred during each game summed across participants. The colors match identified music success groupings: green for musical cultural touchstones done well, blue for musical cultural touchstones done wrong, and red for explicit missed opportunities.

4.1.1 Game comments for musical touchstones done well

The *Strength* game, the standout example of a musical cultural touchstone done well, garnered 17 comments overall (a mix of spoken and written) focused on either enjoying or recognizing the music from *Rocky*. This movie is famous for its training montage set to the song "Gonna Fly Now" and picturing famous landmarks in Philadelphia, where the study took place. Many participants labeled the *Rocky* reference explicitly [e.g., "Hitting the robot while listening to Rocky Music" (Subject 32), "The Rocky punching one was the best!" (Subject 9)]. Video transcripts likewise included references to the movie while speaking to Baxter, e.g., "This is…are you trying to train me like the guy (Rocky)?" (Subject 2). In the end, the Strength game was the most popular of all the games, with 18 participants selecting it as their favorite. It also led to significantly more exercise than any other game aside from Agility, as further reported in our past work (Fitter et al., 2020). Verbal comments about the game doubled down on this success at energizing participants, e.g., "Hahaha! This is fun!" (Subject 9), "That's it?! Man!! I could go on for days!" (Subject 9), and "I like that one. It (…) pumped me up!" (Subject 2).

4.1.2 Game comments for musical touchstones done wrong

Compared to the above case, using a musical cultural touchstone that is not recognized by the user base misses the mark. The *Flamenco* game was based on a well-known guitar song, Malagueña, but the participants seemed to be unfamiliar with it. Only three people commented on the song, using the quick descriptors "great music" (Subject 37), "good music choice" (Subject 4), and "cheesy" (Subject 39). Relative to this count, more game comments (five in total) focused on participants' self-assessed weaknesses at dancing. In the end, although it did not lead to any notes on technical deficiencies, Flamenco was not chosen as a favorite game by any participants. It also was among the bottom group of games for exercise induction. Spoken comments on this activity varied from "That was hard!" (Subject 27) to "That's it? This is easy! (laughter)"

(Subject 2), or even prescription to someone else as a better potential user [e.g., "my daughter would love that" (Subject 34)].

4.1.3 Comments for games with missed musical touchstone opportunities

Among other musical games, nine comments indicated a desire for more familiar music. Responses to the *Stretch* game included "I want something I recognize. Even if it is a children's song" (Subject 7), "It didn't sound like anything though…" (Subject 20; the one verbal response), and "Music was not very celebratory" (Subject 39). One participant noted that the *Teach* game "may be more exciting if (it) had a popular tune to compose or song to follow" (Subject 6). Experiences were not fully one-sided; some verbal feedback on the game was positive [e.g., "Kinda cool to play with!" (Subject 10)] while other notes showed displeasure [e.g., "I feel like this is really weird" (Subject 21), "that's not pretty" (Subject 9)]. In the end, two participants chose each of the above games (Stretch and Teach) as their favorite, and both games were among the lowest tier of games for exercise promotion.

No explicit comments addressed the *Mimic* game music; since it entailed only drum sounds, it may be perceived as belonging to a different musical realm than the other musical games. Regardless, game comments for the Mimic game uniquely hinted at feelings of accomplishment or self-efficacy; some participants liked the game because "you kind of taught (the robot) something (during the Mimic game)" (Subject 33) or rose to the challenge, proclaiming "I beat him! After the fourth time" (Subject 27). At the same time, Mimic was the third most popular game (with five selections), although it appeared to be more cognitive than physical in terms of exercise; it tended to be the lowest in terms of exercise level production. Incorporation of a strong musical touchstone might make this exergame even more effective.

4.2 Social experience and immersion

The second overall theme seems to be another potential reason for the disparate perception of games with similar mechanics. This topic, social experience and immersion, is a shorthand for how clearly the user understood and accepted the intended social role of Baxter (the social analogue) in each game, as described in more depth in Section 3.2.4. Immersion is a common video-game idea that aims to describe a loss of self-awareness and richness of interaction experience (Desurvire and Wiberg, 2009; Jerzak and Rebelo, 2014). For exergames, past work supports the idea that flow is likewise a helpful feature (Huang et al., 2018); for example, becoming engrossed in an activity could help users forget that they are carrying out repetitive motions. Looking across social games, participant comments hinted at three different tiers of implementation success:

- Social analogue understood and accepted: Agility, Roboga, Strength
- Social experience understood, but not accepted: Flamenco, Handclap
- Social experience not clearly understood: Mimic, Stretch

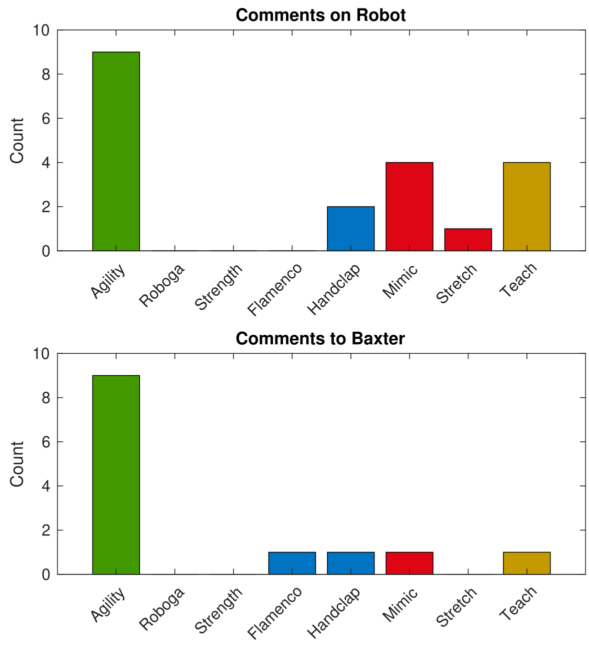

FIGURE 3
Number of verbal comments about and to Baxter made by all participants during each game. The colors match social engagement success groupings: green for social analogue understood and accepted, blue for social analogue understood but not accepted, red for social experience not clearly understood, and yellow for no social analogue.

For some games, players recognized the analogy but failed to buy into the interaction paradigm, and for other activities the underlying social idea was lost altogether. On the other hand, sometimes both of these aspects of the social interaction design went smoothly. Below, we share evidence that led to the proposed sorting of games alongside incidence levels of comments about and to the robot, as shown in Figure 3, which seem to have inherent connections with the general social experience. While considering social interactions with the robot, it is worth briefly noting that although the study script used "it" pronouns to refer to Baxter, most participants used male pronouns to describe the robot; similar tendencies to gender robots have also appeared in past related work (e.g., Stroessner and Benitez, 2019; Søraa, 2017).

4.2.1 Social experience and immersion success

The thematic analysis indicated that Agility, Roboga, and Strength were all successfully interpreted as their intended social analogues and seemed to immerse users effectively. During the *Agility* game, two users explicitly labeled the interaction as similar to waking up a deeply slumbering family member. One compared the interaction to "waking up my son, who loves to sleep (and is) a bit difficult to wake up" (Subject 27), and another noted "He's like one of your child…your children. Get up! Get up! You can't sleep!" (Subject 16). Another participant mentioned that the "robot is a heavy sleeper" (Subject 20). Similar to typical behaviors while trying to wake a friend or family member from sleep, this game led to the most instances of mid-game talking to the robot (nine of 13 total instances across games) and about the robot (nine of 20 instances). Much of the dialog with the robot was playful, such as "I should've just thrown some water on him. That'd be easier" (Subject 30) and "Wake up! Don't make (me) use bad language!" (Subject 31). The smooth social experience of the game may have contributed to the popularity of the activity (second most favorite of the games, with six selections) as well as the high exercise level; Agility led to significantly more exercise than any other game, as further reported in Fitter et al. (2020).

Roboga likewise led to interpretation of the activity as intended, as well as to creation of an immersive experience. Several participants labeled the activity as yoga explicitly [e.g., "Reminded me of yoga" (Subject 18), "It's like yoga" (Subject 10), "It was very calming. It felt like yoga" (Subject 15)]. Further, one user expressed interest in the broader use of the robot as a yoga partner during this game [i.e., "I think it could be fun to do yoga w/Baxter" (Subject 24)], and another person declared "Thank you, Baxter!" (Subject 27) at the end of the activity, in a similar way that one might do at the end of an exercise class. Unlike the Agility game, Roboga did not lead to any instances of the participant talking to or about Baxter during the game; however, this is authentic for the intended type of exercise experience. It would be unusual for someone to begin chatting with a classmate or instructor during yoga class. Roboga led to four selections as favorite game and a moderate amount of exercise (i.e., more than Mimic, and not significantly less than Strength).

Finally, the *Strength* game seemed to succeed in terms of both social experience and immersion. Participants noted the boxing premise specifically in comments like "I want Baxter to be my boxing coach" (Subject 24), "Boxing with Baxter was engaging" (Subject 27), and "That was fun! They should call it [the robot] "Boxter" (Subject 5). As might be expected with the boxing context, participants appeared to be more focused on the physical aspect of the game than bantering with the robot during the activity; there were no mid-activity comments to or about the robot. This flowing social experience may have bolstered the popularity of the game; as mentioned previously, Strength was the most common choice of favorite game, and it led to one of the highest exercise levels.

4.2.2 Social experience without immersion

Two games, Flamenco and Handclap, fell into this next category of activity recognizability without full buy-in. For *Flamenco*, people understood that they and the robot were dance partners, noting "I have to brush up on my dance moves!" (Subject 40) and "I performed just like in real life - never could follow someone on the dance floor": (Subject 38). But something felt off about the interaction, e.g., one user commented "It feels a bit awkward dancing so slowly" (Subject 7); technical limitations prevented implementation of faster robot dancing. Perhaps in part because of this lack of immersion, Flamenco led to just one comment to the robot during gameplay (in addition to being the least favorite and among the lowest inducers of exercise).

The *Handclap* game was easy to interpret as such, but something likewise felt wrong in its flow. One participant noted that it is "easy to play (a) clapping game with (a) human, but (they) had difficulty remembering Baxter's routine or predicting which hand (would go) which direction" (Subject 2). Relatedly, one user needed to think so hard about the instructions that they repeated key ideas back to themselves aloud [e.g., "When the hands are up top he's done. Okay" (Subject 27)], and another participant misunderstood Baxter's motions, asking, "Is it a hug? can I get a hug?" (Subject 31). Dialog to and about the robot sometimes occurred during this game, but it usually centered on the user's lament about or surprise at their own bad performance, e.g., "Baxter dude, I didn't do too good" (Subject 38) and "Oh! Baxter! Why do you look sad!?" (Subject 31). Two participants chose Handclap as their favorite game, and this activity was among the lowest tier of games for exercise promotion, although it tended to be near the top of this group.

4.2.3 Social experience not well understood

In other games, namely, Mimic and Stretch, the analogy to everyday social experiences was not clear. Participants still found enjoyment in *Mimic*; for example, one user mused that they "enjoyed being able to teach Baxter" (Subject 24). This observation indicates some understanding of the activity premise, but not a strong connection to the light-up Simon toy analogue. At the same time, this game inspired a moderate amount of commenting about the robot's end-of-game response, which playfully teased participants in different ways. Nevertheless, Mimic was one of the most common game favorites, although it did not lead to much physical exercise.

The *Stretch* game failed to conjure any successful ties to hand-tag-like childhood games, although one participant saw the potential for a clearer analogy, noting that "avoiding my high-five would have been more engaging" (Subject 8). There was only one comment about the robot during the gameplay [i.e., "Oh! It didn't like that" (Subject 1), when a hand contact failed to register correctly]. Interestingly, this is one of the few times when a user labeled Baxter with the pronoun "it." As highlighted before, Stretch was near the bottom of the game group for both selections as favorite and exercise production. A stronger social analogue could increase the effectiveness of both of these games.

4.3 Gameplay clarity

A final influential theme in the thematic analysis, and apparently a key to user experience, was feedback on gameplay clarity. It seemed that certain aspects of gameplay clarity could make or break the success of activities in terms of user experience and induced exercise. A subset of games appeared to be highly clear in terms of gameplay, others had selected flaws that did not prove to be dealbreakers, and the final group were so flawed that issues in gameplay clarity interfered with us learning much else about the game. Participant comments indicated the following breakdown:

- Gameplay clarity done well: Flamenco, Roboga, Stretch
- Explicit gameplay clarity improvements noted: Agility, Mimic, Strength
- Gameplay clarity done badly: Handclap, Teach

This split may indicate that the gameplay mechanics do not need to be perfect (in fact, the three most common favorite game selections are in the middle category), but there is a level of confusion and difficulty from which there is no redemption (i.e., the final category).

We consider these clarity groupings alongside the number of times participants needed to try the game to achieve a successful interaction and video coding results that showed objectively how many times each participant asked clarifying questions about the

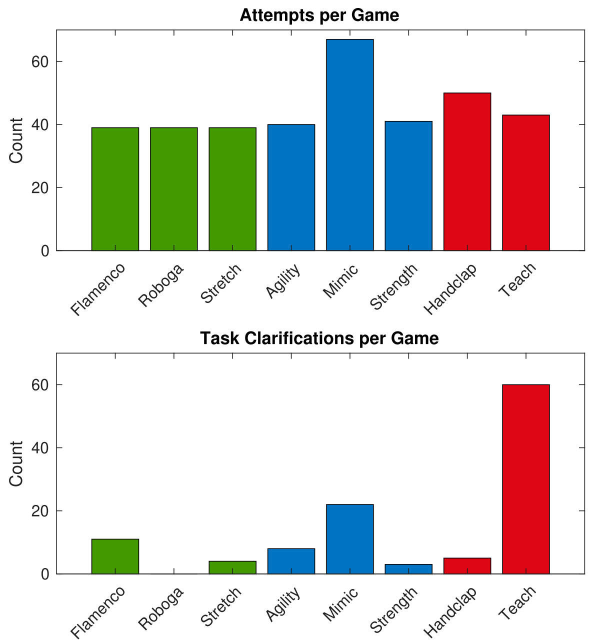

FIGURE 4
Number of attempts and task clarifications for each game. Note that the expected number of attempts for a participant (if all goes correctly) is 1, which would lead to 39 or 40 total attempts for each game. The colors match identified gameplay clarity groupings: green for gameplay clarity done well, blue for explicit gameplay clarity improvements noted, and red for gameplay clarity done badly.

task, as shown in Figure 4. These data streams are supplemented by counts of the different types of errors participants made while playing each game, as reported alongside results below. These pieces of information taken together reveal more about what types of confusions are forgivable and how our exercise games might be improved in the future.

4.3.1 High-clarity game success rates and errors

Based on the inductive analysis, the Flamenco, Roboga, and Stretch games all seemed to be high-clarity games. For each one, only a few corresponding critiques related to clarity issues, which we take to mean that the mode of play for each game was (at the very least) not unclear to participants. Most of the *Flamenco* comments centered on potential improvements to the feedback provided by the robotic system [e.g., "It was hard to tell with the music when to start the dance motions" (Subject 9)]. For *Roboga*, one comment showed potential for a clearer match between the user's body and Baxter's pose, i.e., "I think the red pads were like the palm of the hand to help determine hand position" (Subject 37). The *Stretch* notes included a suggestion to increase the system volume slightly.

4.3.1.1 Task clarifications

The above observations from the raw data align well with the count of task clarification codes that were noted in the video recordings for each activity. Roboga had the fewest task clarifications, with zero. Stretch was among the three lowest with four of this code, and Flamenco was closer to the middle of the group with 11. These clarification requests did not directly reflect problems in gameplay clarity, but there is likely a close connection between observed clarity issues and participant questions to check that they are playing the game correctly; the latter reflects the meaning of this code. No participants needed an additional attempt for any of this grouping of games.

4.3.1.2 Success rates and user errors

As far as game completion success goes, every participant reached the end of the Flamenco game, but we observed assorted dance motion errors performed by participants. In ten cases, users added an extra move while dancing with the robot (across participants, 0.3 ± 0.8 extra moves, with a maximum of four for any given participant). Participants also missed a dance move 29 times (over participants, 0.7 ± 1.8, with a maximum of eight) and performed an incorrect move in their dance sequence 44 times (over participants, 1.1 ± 2.2, with a maximum of ten). As shown by these error distributions, Flamenco mistakes arose more frequently for just a subset of the participants even though the game premise was clear. Added feedback about the correctness of dance moves might have reduced the occurrences of these errors.

All participants successfully completed the Roboga game, but we noticed two types of errors wherein participants either did not follow the verbal game instructions or did not follow Baxter's example. In 34 instances overall, participants failed to relax their arms during the brief relaxation period between sets of held poses. Across participants, this constituted 0.9 ± 1.6 failures to relax, where three was the maximum number for any one participant. This behavior actually just led to extra exercise, but it could be considered one type of participant error, likely stemming from the fact that Baxter's arms cannot hang straight down as human arms can. There were also 52 cases when the participant's pose did not accurately match Baxter's pose, almost always due to differing orientations of the palm (across participants, 1.3 ± 1.2 mistakes, with a maximum of four for a single participant); this type of error matches the participant comment about hand orientation ambiguity.

In the Stretch game, participants were uniformly successful at playing and completing the game. The only recorded error during this game was an error in the robot's sensing strategy; during one move, the participant seemed to contact the robot in the correct way, but Baxter's accelerometer-based contact detection strategy did not successfully identify the hand contact. This game appeared to be easy to play, but not necessarily engaging.

4.3.2 Medium-clarity game success rates and errors

In the next category, Agility, Mimic, and Strength seemed to be medium-clarity games. For the *Agility* game, comments focused on being unsure how hard or fast to hit the pads, as well as wanting a more continuous spectrum in the facial responses to see their progress, e.g., "The lack of a continuous color scale makes it difficult to see if progress is being made" (Subject 8). Most of the *Mimic* comments were about clearer cues for who had lost or won the game, and when this occurred. The *Strength* game comments focused on the other sounds making it hard to hear the bell cue, and thus, their reliance on the facial cues for timing, such as "Could not hear bell to strike pads. Watched for green face" (Subject 23).

4.3.2.1 Task clarifications

The task clarification rate matches the above list closely with one exception. Agility and Strength both led to very low numbers of task clarification instances (eight and three, respectively). On the other hand, Mimic led to the second highest number, at 22. This result may indicate that although the idea behind the Mimic game (pattern teaching, matching, and building) was familiar, the underlying mechanics were not clear enough (i.e., 12 users had clarifying questions about this game, with up to four questions coming from the same person). Similarly, 18 participants needed a second attempt when playing the Mimic game, after misunderstanding the low-level game mechanics during the first try. No users needed more than one attempt to play the Agility game, and one user needed a second try at the Strength game.

4.3.2.2 Success rates and user errors

In terms of game completion success, in the Agility game, only one of our 40 participants failed in the central task of waking the robot up. This individual tried the activity twice and then decided to give up at the game, resulting in a 2.5% failure rate overall. Seven participants exhibited one additional behavior that revealed potential confusion about the gameplay; they continued to hit Baxter's arms even as the robot began yawning, stretching, and waking up. This error sometimes seemed to be playful and deliberate.

30 study participants won their final trial of the Mimic game, and nine lost. Of these recorded losses, six were due to the participant forgetting their own pattern and making a mistake, and three were due to Baxter declaring victory after a false positive or false negative hand contact. An additional user made a clapping pattern error simultaneously with a robot error, leading this trial to be recorded as a win for the human user. Thus, we consider seven of the trials true user losses; this 17.9% failure rate was the highest of any game. At the same time, this game was the third most popular overall; we discuss why this might be the case later in the paper.

Baxter's end-of-game facial expression and body language was a high-level indicator of participant score in the Strength game. 39 users achieved the highest score bracket possible, and one participant received the "neutral" final reaction from Baxter, indicating that they just barely completed the game successfully. This game also led to one unexpected participant tendency: several users struck Baxter in a rhythmic pattern matching the beat of the *Rocky* song, rather than delivering a one-two punch when cued by Baxter. This behavior was similar enough to the expected gameplay that this discrepancy did not lead to difficulties completing the game.

4.3.3 Low-clarity game success rates and errors

The final low-clarity category included Handclap and Teach. Based on the inductive analysis, there seemed to be multiple layers of trepidation about required input from the user and correct performance of these games. The comments for the *Handclap* game focused on the cross-clap being difficult to differentiate from the normal single clap and the transition from demonstration to collaborative clapping being unclear. For the Handclap game in particular, this lack of clarity overran the familiarity of the game premise. Participants had particular difficulty distinguishing between types of claps [e.g., "I kept confusing the cross hit for the regular one" (Subject 33)]. The Teach game comments focused on general uncertainty about musical performance skill, not being able to hear the note before selecting it, and not being able to listen to what they have so far for the song. *Teach* led to different points of confusion and frustration, from "(I) was a little confused this time regarding how to make the notes continue" (Subject 19) to "There was no way to hear a chord w/o recording it. Frustrating" (Subject 13) (a point of critique for three different users).

4.3.3.1 Task clarifications

In this game grouping, we see the incidence of Teach game clarifying questions matching well with the thematic analysis. Teach led to the highest overall number of clarifying questions, with 60 total. On the other hand, Handclap did not lead to many (just five total). This observation may show that while the game itself is not hard to play, there is an inherent flaw in the way it was implemented, as also hinted at in the quotes above. On the other hand, the Handclap game did require an outsized number of tries compared to all other games; 12 participants required a second chance while trying this game, whereas only three participants needed an extra try for Teach.

4.3.3.2 Success rates and user errors

In the Handclap game, we noticed that some participants lost, some claps were missed, and participants did not always contact the robot with the correct hand. 35 participants successfully reached the end of the game, and three lost the game to Baxter. This game's 7.9% loss rate was the second highest of all the games. Even for participants who won the game, some claps were missed; users did not lose the game unless several consecutive claps were missed. 34 total claps were missed by participants collectively. Across participants, this constituted 0.9 ± 1.4 claps missed, where seven was the maximum number of claps missed by a single participant. A more common error was contacting Baxter with the incorrect hand. Overall, 140 claps during the collective trials were performed with the incorrect hand (across participants, 3.7 ± 5.3 incorrect claps, with a maximum of nineteen wrong claps). These error distributions show that mistakes arose commonly across participants during the Handclap game.

The Teach game was very collaborative in nature and had no concrete performance objectives, so we evaluated how many chords were recorded and explored by participants (a measure of how much participants engaged with the game). Song length was 17.4 ± 19.4, where songs ranged from three to 121 recorded notes. Most participants tried deliberately to create a song, while a few explored chaotically.

5 Discussion

In conjunction with framing information on favorite game selections, induced exercise levels, and video annotations, the inductive analysis results paint a picture of why certain games were more successful than others in terms of user experience and induced exercise levels; they also suggest promising ways to design robot-mediated exercise activities in the future. In this section, we discuss key findings from the inductive analysis results and highlight potential takeaways (typeset in italics) for the design of future human-robot exercise games. For those interested in our exercise games in particular, we also encourage a close review of the game improvement suggestions in Supplementary Appendix SB. We conclude with key strengths and weaknesses of the work, followed by final thoughts.

5.1 Musical cultural touchstones

The music-focused theme that arose from the inductive analysis is a possible explanation for why the Strength game was so successful on both the user-experience and the exercise-level fronts, despite its simple and repetitive premise. The great popularity of this game goes against the idea of repetitive games leading to disengagement, which implies the possibility that building cultural references into robot-mediated exergames will improve user engagement. This observation is similar to the finding of Lyons et al. (2011) that games using licensed popular songs were most enjoyable to users. It also aligns well with past work on music in exercise generally, which shows that music can help to heighten physical activity levels (Clark et al., 2016; Karageorghis and Priest, 2012; Wiemeyer, 2012), and that the selected music should be congruent with characteristics of the user, task at hand, and workout goals (Karageorghis, 2020).

Other games did not succeed in their musical references (i.e., Flamenco) or missed opportunities for introducing cultural references (i.e., Mimic, Stretch, Teach). The song Malagueña was not nostalgic for most participants, although it might be relevant in other cultural contexts; for example, one employee who worked across the hall from the study site noted that they loved hearing the song playing due to their Cuban cultural heritage. Disappointed comments on the recognizabilty of Stretch and Teach game music demonstrates an important focus on cultural touchstones for game success. Taken together, these results support the idea that musical cultural references can be used as a method for rapidly building game enthusiasm and engagement. In the cases of our exercise games, we hypothesize that games using more familiar music for the cultural context of the study (in our case, a large urban center in the United States) would inherently be more popular than those without this musical connection. This idea could be tested further in follow-up work, both within and beyond our use case.

5.2 Social engagement and immersion

Data surrounding this second theme may reveal why the Agility game was the second-most-popular activity, despite being even simpler than the most-popular Strength game. Again, this game was extremely repetitive and had one of the simplest premises in our set of games (waking up the robot). We believe the key for Agility may be found in the relatedness and immersion themes from video-game research (Vahlo and Hamari, 2019), which seem to tie to the social context recognition and flow experience observed in Agility (as well as the previously discussed and popular Strength game and the reasonably popular Roboga game).

The social analogue underlying the Agility game was quite clear to participants, and several users directly articulated the interaction metaphor underlying the activity. The same was also true for Roboga and Strength. One difference across these socially engaging games was the amount of instigated speech to and about Baxter as a result of gameplay; Agility commonly prompted these actions, while Roboga and Strength did not. At the same time, these user behaviors match typical norms in the corresponding social scenario analogues.

Flamenco and Handclap were recognizable as their design metaphors, but something was off for each of them, which seemed to prevent a fully immersive experience. In Flamenco, this missing link may have been a result of the song selection; for example, regionally relevant line dances like the Cha-Cha Slide or the Wobble may have been better choices for promoting a flow experience. Users recognized the similarity of Handclap to childhood hand-clapping games, but without the self-clapping motion common to these games and the typical back-and-forth flow (design choices made to smooth the sensing system side of the game and make the experience sufficiently different from other games in the set), something seemed to be amiss.

The final socially designed games were not perceived in a nostalgic social way at all. Participants understood that they were teaching a pattern or following Baxter's actions for Mimic and Stretch, respectively, but the activities did not conjure up any connection to familiar experiences. One way to inspire a more social connection to the Mimic game could be to lean into the "Simon" game analogue (for example, by having four action options, using the colors red, blue, green, and yellow to each correspond to one move, and including "beep" sounds akin to those of the original electronic game). As suggested by participants, a more playful behavior paradigm such as Baxter overtly trying to avoid the user's hand may have made the Stretch game more successful.

A final social engagement note is that our results show that *users will interact with a robot in a social way even if it is nonverbal.* In socially assistive robotics, robots most commonly use natural language to communicate. The addition of speech to a robotic system can be a double-edged sword; it can add clarity to communication, but it also tends to increase the user's expectations of what a robot is capable of (often beyond the realm of the realistic) (Kwon et al., 2016). Even without speech, participants reacted socially to Baxter (particularly in the more challenging games) with chiding, encouragement, pleasantries, apologies, banter, and gendering. We believe part of this success was due to the system's facial expressions (easily customized with the face screen), as well as other social cues integrated into the games. This finding echoes existing knowledge from human-robot interaction; past studies (e.g., Fong et al., 2003; Epley et al., 2007; Krach et al., 2008) likewise indicate that humans tend to react in a social way to robots whether or not these systems are intentionally designed to be social. A new aspect of the current work is gaining this type of understanding for social exercise gameplay with industrial collaborative robotic systems like the Baxter robot in particular.

5.3 Gameplay clarity

The final theme from the inductive analysis showed that Flamenco, Roboga, and Stretch were clear games in terms of the users naturally understanding what they need to do for gameplay. Agility, Mimic, and Strength were partly clear with moderate potential for improvement, and Handclap and Teach were not clear. In general, high-clarity games tended to be very similar to the traditional imitation-based interactions that are commonly used in socially assistive robots (Pulido et al., 2019; Guneysu and Arnrich, 2017; Shao et al., 2019; Bäck et al., 2013; Görer et al., 2013; Matsusaka et al., 2009; Lewis et al., 2016). At the same time, most of the top-selected favorite games were in the middle clarity category (i.e., all but Roboga). This contradiction may signal the importance of having compelling references and social experiences as part of gameplay design, in addition to hinting that minor clarity problems can be forgiven within the context of a game that has other appealing design elements.

Our results show that participants were generally successful at completing the exercise games. The majority of participants completed or won every exercise game. Across all participants, we recorded only thirteen instances of participants losing games. Additional robot errors (seven robot sensing errors in the Mimic game and one in the Stretch Game) and participant errors (continuing to hit the robot after the Agility game had ended and making movement errors in the Flamenco, Handclap, and Roboga games) highlight specific opportunities to update our robotic system and improve the guidance that participants receive during games. For example, feedback on the correctness of Flamenco dance moves and Roboga poses would likely lead to higher movement accuracy; a camera-based markerless motion-capture system could be used to enable real-time assessment of such movements (Mohan et al., 2021).

5.4 A note about the mimic game

Among the four most popular exercise games (i.e., Strength, Agility, Mimic, and Roboga), the preference of users for Strength, Agility, and Roboga is well explained by the above thematic analysis information, but it is not yet clear why the Mimic game was so favored. One potential explanation is the feeling of accomplishment that users gained after mastering this more cognitively focused game, especially after failing to succeed in the initial attempt (as was the case for 18 participants). Among other activities, this game may have been more mentally engaging. We encourage robot-mediated exergame designers to consider a similar blending of physical and cognitive activities as one potential strategy for promoting game success (even in cases lacking in nostalgia or social references).

5.5 Key strengths

The results presented in this article move beyond our game-specific findings in Fitter et al. (2020) and toward a way to think about exercise games that may be more generalizable. Interested researchers could potentially build from our proposals about why the four most popular games were favored as such, using these ideas as hypotheses for future empirical work. We believe that the results indicated herein—that musical cultural references and socially engaging premises can supercharge robot-mediated exercise, and that these factors may even outweigh the clarity of gameplay—are crucial and merit careful consideration by both the rehabilitation robotics and the socially assistive robotics communities. Participants were typically successful in completing the exercise games, appearing to feel accomplishment particularly after winning a challenging game. Other researchers with a Baxter robot can apply this work directly by leveraging our open-source game repository (Fitter, 2020); specific lists of suggestions for further game iteration appear in Supplementary Appendix SB. The proposed games (especially with the recommended modifications) have the potential to positively impact human health by encouraging exercise.

5.6 Limitations

The study design was not without limitations. For example, the Strength game was so popular that opinions on this activity sometimes overwhelmed the responses to the other games. While this enthusiasm is a positive sign for using cultural references to build engagement, this effect could make examining what aspects of other games were engaging more difficult. The presence of a research team member during the study helped participants navigate games, but it also resulted in a potential increase in user confidence and comprehension during the games. In the future, it would be ideal to allow users to learn and play games independently (e.g., through instructions delivered via a tablet near the robot or through feedback provided by the robot itself) to gain a better understanding of how a system may be used outside of a lab setting, e.g., Mohan et al. (2021). This change to more independent gameplay, likely in less-structured environments and without closely linked compensation, could result in a lower chance of demand characteristics in the study design. There are also potential benefits of using wearable sensors to record user arm movement and physiological signals for objective measures of exercise, smart difficulty-level adaptation, or biofeedback. The reported level of exercise of participants was relatively low, despite the goals of the work. In the current work, we prioritized allowing users to be successful in their gameplay, which may have led to these lower exercise levels. In the future, we anticipate that we could simply increase game difficulty to yield greater exercise. Although the user population was diverse, we mostly lacked participants in the middle-age range, and we did not collect specific enough demographics to replicate (for example) the distribution of participant socio-economic status. The short-term and in-lab nature of the study also limit our understanding of the studied exergames; longer-term study in the wild and with more diverse users is needed to better investigate how the games perform and whether they see use past the point of novelty.

5.7 Conclusion

Overall, the results of this work show the promise of recognizable music and immersive, socially familiar experiences for robot-mediated exergames, in addition to hinting that engaging interactions require at least a moderate level of gameplay clarity. Importantly, cultural and social touchstones can be designed independently of the game mechanics and overlaid on a wide variety of games. The reasonably popular Mimic game further demonstrates that challenging activities that are nevertheless achievable for users may hold merit for exergame design. Although these ideas are already established for game design in general, they are not yet well-understood within the rehabilitation robotics space. Accordingly, there is a need to confirm that ideas of this type will replicate between application domains, and rehabilitation robotics researchers must assess whether and how existing game principles transfer to exergames. Researchers working on related topics should consider what our work suggests about the benefits of musical cultural touchstones, social experience, and immersion in the robot-mediated exercise game space. Although recent work has made strides in this area, the historical tendency in most rehabilitation robotics work has been to focus more on the physical mechanisms and control systems, and less on the social user experience. Our work indicates that a mix of reasonably clear system usability and some added social dimension is best to engage users, even in cases when one type of exercise is most important to the patient's medical needs (e.g., the physical needs of someone with stroke or the cognitive needs of a user with dementia). This insight agrees with past assistive robotics work (e.g., Fasola and Matarić, 2012; Kashi and Levy-Tzedek, 2018) and signals a need for careful consideration of such a blend in rehabilitation robotics more broadly.

Data availability statement

The datasets presented in this article are not readily available because the video and text data that is the focus of the current article cannot be shared while ensuring anonymization of participant identity. However, most materials associated with this work are available for easy replication. A video explaining each exercise game is available here: https://www.youtube.com/watch?v=5zlaqlJJpts&feature=youtu.be. Individuals who are interested can download the source code for our exercise games here: https://github.com/shareresearchteam/baxter-exercise-games. In this repository, we include details on how to launch the exercise games in the same way that we did in our study. Requests to access the datasets should be directed to NF, naomi.fitter@oregonstate.edu.

Ethics statement

The studies involving humans were approved by the University of Pennsylvania Institutional Review Board under protocol number 826370. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

NF was responsible for experiment preparation, data acquisition, data processing, and publication writing. MM supported data collection, data analysis, and publication writing. RP contributed to data analysis and publication writing. MJ and KK advised throughout the experiment preparation, data acquisition, and data processing, and also supplied revisions for each publication draft. All authors contributed to the article and approved the submitted version.

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Conflict of interest

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frobt.2023.1155837/full#supplementary-material

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NeuroAIreh@b: an artificial intelligence-based methodology for personalized and adaptive neurorehabilitation

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Cognitive impairments are a prevalent consequence of acquired brain injury, dementia, and age-related cognitive decline, hampering individuals' daily functioning and independence, with significant societal and economic implications. While neurorehabilitation represents a promising avenue for addressing these deficits, traditional rehabilitation approaches face notable limitations. First, they lack adaptability, offering one-size-fits-all solutions that may not effectively meet each patient's unique needs. Furthermore, the resource-intensive nature of these interventions, often confined to clinical settings, poses barriers to widespread, cost-effective, and sustained implementation, resulting in suboptimal outcomes in terms of intervention adaptability, intensity, and duration. In response to these challenges, this paper introduces NeuroAIreh@b, an innovative cognitive profiling and training methodology that uses an AI-driven framework to optimize neurorehabilitation prescription. NeuroAIreh@b effectively bridges the gap between neuropsychological assessment and computational modeling, thereby affording highly personalized and adaptive neurorehabilitation sessions. This approach also leverages virtual reality-based simulations of daily living activities to enhance ecological validity and efficacy. The feasibility of NeuroAIreh@b has already been demonstrated through a clinical study with stroke patients employing a tablet-based intervention. The NeuroAIreh@b methodology holds the potential for efficacy studies in large randomized controlled trials in the future.

KEYWORDS

neurorehabilitation, virtual reality-based activities of daily living simulations, artificial intelligence in health, profile dynamics, knowledge representation and reasoning applications, stroke

1 Introduction

According to the World Health Organization, dementia and stroke are among the leading causes of disability and dependency. By 2050, the percentage of older people should increase by 35%, which raises the number of people at risk of developing dementia from any etiology (1). Up to 53.7% of all cases of dementia are assumed to be due to Alzheimer's disease (AD), while 15.8% are considered to be due to Vascular Dementia (VD) (2). With, so far, no effective pharmacological treatment found, the increase of older adults with cognitive impairments makes it urgent to deliver adapted/personalized neuropsychological interventions in individuals with Mild Cognitive impairment (MCI), a clinical condition that increases the risk of developing dementia in 38% (3); and stroke, which likelihood to develop VD is estimated to range from 36 to 67% (4).

The Neuropsychological Assessment (NPA) is a comprehensive evaluation of an individual's cognitive, emotional and behavioral functions, typically conducted by a neuropsychologist. It involves a variety of instruments to assess different aspects of brain function, such as memory, attention, language, and executive functioning. NPA is often performed in clinical settings to diagnose and treat conditions such as acquired brain injuries, neurodegenerative diseases and psychological disorders. NPA is essential to determine a patient's cognitive profile. An Assessed Cognitive Profile (ACP) refers to the formal measurement of an individual's cognitive abilities and functioning. This profile includes information about various aspects of cognition (memory, attention, language, and executive functioning) and outlines an individual's strengths and weaknesses in these domains. The ACP is valuable for various purposes, including diagnosing cognitive impairments, monitoring changes over time and/or guiding intervention strategies, making it a crucial component in healthcare and education settings. However, its paper-and-pencil methodologies have fallen reliant on labor-intensive procedures of data collection that provide relatively data-poor estimates of human behavior despite the rapid technological advances in other healthcare fields (5). Integrating technology, namely artificial intelligence (AI) methodologies, into NPA practices has tremendous potential to advance the field faster in numerous areas, such as neurorehabilitation (6).

Technology-based assessment and rehabilitation methods with high ecological validity, particularly those based on the use of Virtual Reality (VR), have been shown to lead to increased outcomes in neurorehabilitation (7). One reason for this could be the fact that VR-based methods allow incorporating cognitive tasks within the simulation of Activities of Daily Living (ADLs) and the creation of well-controlled environments oriented toward the needs of patients (8–10). Reh@City, a VR-based neurorehabilitation tool, is an example where memory, attention, language, and executive functions tasks are integrated into the performance of several ADLs (11). A randomized controlled trial with stroke participants who underwent rehabilitation with the Reh@City revealed a significant impact on cognitive and functional domains compared to equivalent standard paper-and-pencil tasks (12).

Recently, a questionnaire was delivered to healthcare institutions in Portugal to understand the actual perspective of health professionals on using technologies for cognitive rehabilitation (CR) (13). Data from 116 participants showed that health professionals mostly use games, puzzles, and paper-and-pencil tasks. Concerning the profile of patients undergoing CR, dementia and stroke were reported as the main conditions being addressed, and most patients were above 60. Results indicated that technologies are not yet widely used by health professionals in CR sessions, with most participants (65.5%) reporting no experience with CR technologies. The most mentioned barriers were the nonexistence of technologies at the institution and the lack of qualified human resources to support them.

The limited adoption of computer-based NPA and neurorehabilitation (14) might be explained by the fact that, rather than incorporating many of the advances in neuroscience or computer science, most test developers redesign paper-and-pencil methods for administration on the computer (5). Although digitizing current tests certainly has advantages over its analog tests, these could be leveraged far more effectively if development efforts also focused on capturing more behavioral data and increasing the ecological validity of tests (15).

Over the last decades, AI capabilities have grown exponentially, and, in recent years, it has become ubiquitous. It is everywhere, from cars to smartwatches, from smart TVs to the operation room in advanced hospitals. Martens et al. (16) identified in their work that, as performance increases, the readability decreases. They ordered AI systems from less performance to most performance: Rule-based Systems, intrinsically linear models, and Artificial Neural Networks/Support Vector Machines. The application of Machine Learning (ML)-based methods in healthcare is also rapidly evolving with practical implications in the prevention, diagnosis, treatment, and prognosis of specific clinical conditions (17, 18). To the best of our knowledge, only three neurorehabilitation platforms are using an AI-driven approach to adapt and personalize training sessions: the Guttman Neuropersonal Trainer (GNPT) (19), the Neuro-World (20), and the Brain Training System (BTS) (21, 22).

The GNPT consists of a tele-CR platform for patients diagnosed with Acquired Brain Injuries (ABI), aiming to provide neuropsychologists services beyond the clinical setting and increasing the personalization, duration, and intensity of the neurorehabilitation process (19). This platform encompasses telemedicine services and AI for knowledge extraction (e.g., data mining, collaborative environments, and automatic system adaptation to patients' performance). The CR personalization process begins with the performance of a baseline NPA; then, the assessment results are stored in the GNPT system and used to define the patients' cognitive profile. The system proposes a Cognitive Training (CT) therapeutic plan based on this profile. The adjustment of the therapeutic plan (i.e., type of CT tasks and difficulty levels) is performed automatically by the system, according to the patient's performance (23). Regarding rehabilitation content, this platform comprises 95 computerized exercises, targeting several cognitive functions (19).

Concerning the Neuro-World, it is comprised of a set of six mobile games designed to challenge visuospatial short-term memory and selective attention (20). The approach allows self-administration of assessment and remote monitoring of the patient's cognitive status (CS). This process happens by analyzing the patient's game performance and estimating the Mini-Mental State Examination (MMSE) results through ML algorithms. A longitudinal study with 12 stroke survivors with mild cognitive deficits demonstrated that the Neuro-World could estimate the MMSE scores with a low normalized root mean square error (5.75%). An interesting contribution of this work is that assessment and rehabilitation can be combined in the same tool.

Lastly, the BTS uses an algorithm that automatically selects and schedules cognitive training exercises (21, 22). The difficulty level of the exercises is generated around the ACP of the participant, which is updated as the participant progresses. The system uses a scoring system to compare performances in different exercises that are merged according to the same cognitive domain level. A supervision process based on "red flags" is activated whenever the system detects user engagement, compliance, or adherence issues.

The existing AI-driven cognitive rehabilitation platforms have several limitations in common, namely: (1) Limited transfer effect as the cognitive skills acquired through these platforms may not always generalize to real-world tasks, as they often lack ecological validity; (2) Reduced engagement and motivation, as some users may find neurorehabilitation tasks repetitive or uninteresting; (3) Lack of clinical supervision, which could potentially lead to suboptimal progress or user frustration; (4) Focus on a limited range of cognitive domains and; (5) The inappropriate personalization due to a one-size-fits-all approach may not be tailored to an individual's specific ACP.

Here, we present NeuroAIreh@b, a new cognitive profiling and training methodology that uses AI to maximize neurorehabilitation prescription personalization and adaptation. NeuroAIreh@b is being developed within a multidisciplinary environment, combining different expertise fields such as neuropsychology, computer science, game design and AI for health. Here, we will describe the methodology followed to address the challenges posed by the scientific literature in the field and neurorehabilitation clinicians. Specifically, we will explain how we: (1) create an optimal cognitive profile by aggregating the NPA instruments results (according to empirical input from neuropsychology experts) and then (re)calibrate them with the support of ML algorithms; (2) design and developed CTTs that can be prescribed according to the patient's ACP, training objectives and performance in previous CTTs; and (3) adapt the CTTs from session to session according to the patient's performance through the theoretical framework of dynamics of profiles developed in (24), based on Belief Revision (BR) theory (25, 26).

2 Methods

2.1 The framework and its challenges

Neurorehabilitation is the most effective approach to address cognitive deficits (27). However, current tools are (a) challenging to adapt to every patient since they demand the application of an extensive battery of NPA instruments, which results are interpreted manually and often prone to errors in the selection of CTTs, (b) have a high implementation cost, since they involve several sessions performed in clinical environments by neuropsychologists and (c) session to session adaptation to the patient performance is not always performed, which may limit the rehabilitation potential and motivation of the patient.

To address these main limitations, we developed a framework for personalized and adaptive delivery of neurorehabilitation that can be divided into four different components as indicated in Figure 1. In this section, we will describe, at a high level, the processes to be performed in each framework component (numbers 1–9 in the Figure 1) and the challenges involved in its construction.

The patient profiling: this component aims to create a multi-dimensional patient profile that integrates several NPAs to determine a baseline CS.

1. Neuropsychologists use validated NPA instruments to assess patients' cognitive functioning. An NPA instrument is a standard part of integrated medical care and is necessary to prescribe and evaluate (in terms of efficacy) rehabilitation procedures. A comprehensive NPA aims: (i) to measure and assess cognitive abilities, ADLs performance, personality traits, and emotional and behavioral functioning in light of the premorbid functioning of the patient; (ii) to quantify the nature and severity of cognitive and functional deficits, analyzing the symptoms and signs present in the context of the structural and functional integrity of brain functioning, to differentiate normal and pathological cognitive decline (iii) to define a baseline level of performance in cognitive, functional, and emotional functioning domains, which can be examined in a longitudinal registry, through repeated evaluations, thus enabling monitoring of the clinical evolution of the patient, in terms of response to interventions (e.g., CT, psychotherapy, pharmacological therapy) or disease's progression; (iv) to identify personal resources and preserved functions that are useful for planning and implementing compensatory intervention procedures.
   Challenges: To represent profiles, it is necessary to define a formal language. This language will be used for representing the profiles, for expressing their properties, for computing metrics about them and for determining their dynamics. After explaining the general structure, we must identify which cognitive, functional, behavioral, and emotional domains should be considered when creating patients' profiles. Also, it is necessary to specify relevant NPA for a comprehensive and multidimensional evaluation of these domains and determine which socio-demographic information (SDI) to consider for profiling purposes.
2. By aggregating the different NPAs with the SDI of the patient, the system creates an Assessed Cognitive Profile (ACP).
   Challenges: To the best of our knowledge, there is a gap in the literature on integrating data from multiple and heterogeneous NPAs and consolidating it into a consistent cognitive profile.
3. The ACP itself is not sufficient to determine the CS of the patient. It must be compared with the normative data available for each NPA tool.
   Challenges: The normative data for each NPA may be provided for different clinical conditions and are often separated by socio-demographic groups. As well as in step 2,

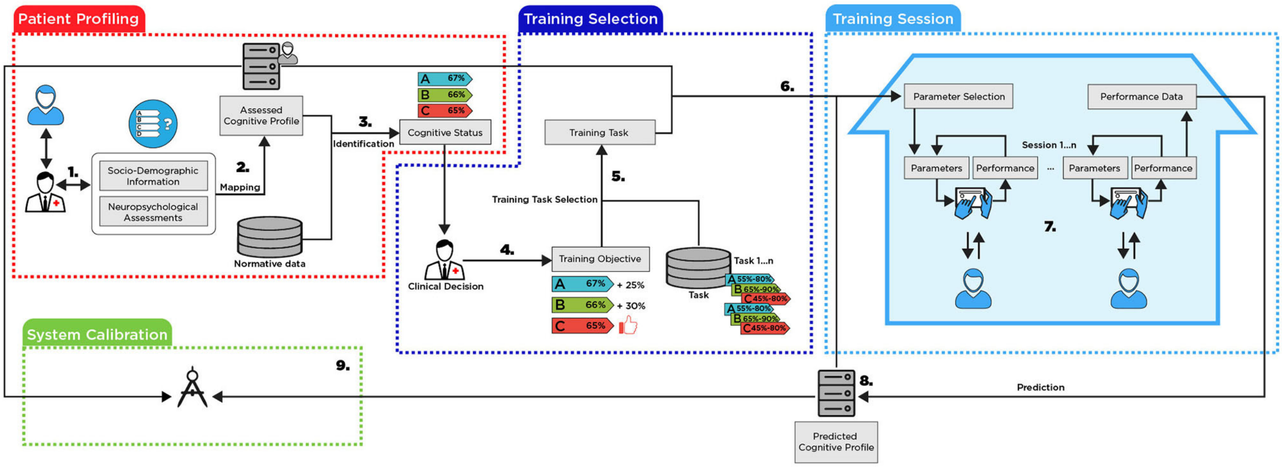

FIGURE 1
The proposed framework.

this needs to be aggregated and compared to the consolidated profile with an objective and quantifiable distance metric.

The training selection: After determining the patients' CS, which gives information about the preserved and impaired domains, neuropsychologists must define the most appropriate CTTs for neurorehabilitation.

4. Based on the patient's CS, neuropsychologists determine specific training objectives for each patient, i.e., in which cognitive domains the rehabilitation training must be focused on to regain or compensate for lost cognitive abilities and functional independence.
   Challenges: The ultimate goal of neurorehabilitation is to help patients to regain independence and autonomy in their ADLs. It can be difficult to establish objectives on a system that will mostly accept numerical values when the objectives are usually set subjectively. The system should be able to perform this translation.
5. After establishing the training objectives and the set of available CTTs in the system, NeuroAIreh@bab will compute which tasks are most appropriate for the training. This is possible since each task has its own profile, i.e., one that details which cognitive domains are required to perform it and how the task's difficulty can be parameterized for the different cognitive domains.
   Challenges: Each task must include information about which cognitive domain it trains. Additionally, it should include constraints regarding the minimal and maximal values for a particular cognitive domain of the suitable patient profile. The set of selected tasks must be optimally provided with the training objective (considering that the number of selected tasks is also limited given the amount of time and number of sessions assigned to the CT program).
6. By combining the initial profile and CTTs, the system establishes the initial parameters for the tasks. These initial parameters determine the task's difficulty according to the different cognitive domains.
   Challenges: Combination is not trivial, and it is based on the tuple ≪task, the value of the cognitive domain in the profile, and associated difficulty≫ that will be adjusted in the system using ML techniques (see System Calibration).

The training session: This part describes how a patient would perform a CT session from the NeuroAIreh@b.

7. The patient can perform his prescribed training sessions at the clinic or at home. Each training session consists of a set of predefined tasks to be executed on a tablet or a personal computer. The NeuroAIreh@b itself will calculate the performance of the patient at each iteration and will redefine its difficulty by changing its parameters to maintain a patient score in a task between 50 to 70% of success to avoid both boredom and frustration, keeping the patients challenged and engaged (28).
   Challenges: To maintain the task score between 50 and 70%, the system must establish a relation between the scores in the different tasks, the task parameters, and the resulting difficulty for each cognitive domain of the patient profile.
8. After a complete training session, the system aggregates the performance in all tasks and estimates if there was evolution or involution in the different cognitive domains of the patient's profile, defining a *predicted cognitive profile.*
   Challenges: Defining the predicted cognitive profile involves multiple challenges. Given a profile representation, defining the profile dynamics when new information is provided is necessary. The system must perform minimal changes in the profile to accommodate the new information. This minimal change requires applying belief revision techniques adapted to the profile representation languages mentioned in Step 1.

The system calibration: This part describes the system's calibration when comparing the predicted profile with newly acquired data.

9. A new NPA is performed when a patient ends a training session and the cycle restarts. The newly assessed cognitive

profile is compared with the predicted cognitive profile of the system. If they differ, the system analyzes the possible causes of the divergence and (re)calibrates the system adequately.
Challenges: The divergences can have different origins: (1) a wrong prediction in step 8; (2) a non-accurate model of the relationship between tasks and cognitive domains in step 5; or (3) a suboptimal adjustment of the parameters in step 7.

2.1.1 The role of artificial intelligence

As previously explained, the implementation of the proposed framework entails several challenges. This subsection briefly describes which parts and AI techniques we use to address the challenges.

The first resort to AI appears in the creation of the ACP [see (2) in Figure 1]. Here, we distinguish two different phases: In order to start with no data, a focus group of six experts in neuropsychological assessment and rehabilitation made an empirical analysis of the NPAs to aggregate them by cognitive domain. This aggregation (a weighted sum) was later checked by using belief merging and judgment aggregation procedures [for an overview, see (29, 30)] and compared with correlations between NPAs, established using ML techniques with available data for Alzheimer's disease, which also involves cognitive impairment. For the second phase, with a fully operational system, and after collecting enough data, we will calibrate the weight assigned to each NPA regarding each cognitive domain and subdomain by ML techniques. All this process is explained in detail in Section 2.2 (The Profiling Challenge). The same approach is used to aggregate the relation between each NPA and the normative data to obtain a consolidated CS.

The second appearance of AI methodology is to optimize the process of CTTs selection from the CTT repository [(5) in Figure 1]. This optimization is explained in detail in Section 2.4.1.

The next resort to AI appears for deciding the difficulty level of a CTT during a training session [(7) in Figure 1]. The CTT parameters must be adapted so that the patient obtains a performance between 50 and 70%. This adaptation is better explained in Section 2.4.2.

The overall training performance comparison along the 12 sessions intervention will be the input for calculating the Predicted Cognitive Profile (PCP) [(8) in Figure 1]. The process of relating the CTTs' difficulty and cognitive domains is not linear, mainly because a CTT trains multiple cognitive domains. It can be challenging to differentiate how much of an obtained performance relates to each specific domain. To create the PCP, the performance of the patient in the training session is transformed into a new entity described in a sentence in formal language (see Section 2.2.1). This constitutes an input for an update function that will actualize the profile, making a *minimal change* to incorporate the new information. The algorithm for this update is based on the theoretical framework for updates of profiles developed in (24).

Finally, the last AI challenge is to calibrate the system. As mentioned in Challenge 9, the divergences can have different origins. In this case, we will collect all the data to identify, via ML approaches, the origin of the divergences.

2.2 The Profiling Challenge

The Profiling Challenge corresponds to Steps 1, 2, and 3 of the framework illustrated in Figure 1.

2.2.1 The profile's structure

In this subsection, we identify which aspects of cognitive, functional and emotional domains are relevant to include in the patient's profile and which NPA instruments are representative of those aspects. We start by defining a formal profile.

Definition 2.1. (24) A profile P is a tuple $\ll label_1, \ldots, label_n \gg$, where $label_i \in \mathbb{N}_0$.

Informally, each element of the tuple of a profile is a characteristic that assumes a finite number of possible values. We have used natural numbers for the content of each $label_i$. However, it is easy to change the definition to use linguistic labels; for instance, if $label_1$ represents the marital status, we can use "single/married/separated/widowed", etc., as possible values.

A simple example of a profile structure is $\ll$age, weight, height$\gg$ and a possible profile is John = $\ll 20, 80, 178 \gg$.

The next step is to define a formal language for expressing the profile properties, for computing metrics about it and for defining its dynamics.

Definition 2.2. (24) A *profile language* is a finitary language $\mathcal{L}$, defined in the following way:

X is a term if and only if:

1. X is a label.
2. If X is a term, then $-X$ is a term.
3. If X and Y are terms, then $X + Y$ is a term.

An atom is an expression of one of the following forms:

1. $X = n$,
2. $X < n$,
3. $X > n$,

where X is a term and $n \in \mathbb{N}_0$. A well-formed formula (wff) is defined as:

1. An atom is a wff
2. If X is a wff, then $\neg X$ is a wff
3. If X and Y are wff, then $X \wedge Y$ are wff

where $\neg$ (negation) and $\wedge$ (conjunction) are the classical negation and conjunction connectives.

$\leq, \geq$ are defined in the usual way, as well as the classical connectives $\vee$ (disjunction), $\rightarrow$ (implication) and $\leftrightarrow$ (equivalence). Backing to the previous example, "weight $\geq 90 \wedge$ height ≤ 180" is a wff.

After defining the profile structure and language, the next step is to define the contents of a profile in NeuroAIreh@b. Therefore, an integration of the relevant NPA instruments, with different weights per domain and subdomains, is essential for a comprehensive evaluation of cognition (see Table 1). For example, screening tests, such as the Montreal Cognitive Assessment (MoCA) (31), are brief multidomain screening instruments to identify cognitively at-risk patients requiring a more comprehensive evaluation. For example, in a domain and subdomain analysis, we have identified the following NPA dimensions in the MoCA: general cognition; orientation; immediate verbal memory; executive functions (namely, working memory, processing speed, verbal fluency and inhibition and visuoconstructive capacity); language (such as comprehension and expression) and sustained attention.

We considered the demographic variables, such as education and age for analyzing the NPA instruments results. The rationale for this option recognizes the impact of these variables in explaining the variance of results and defining the test scores' normative benchmarks. From a rehabilitation perspective, it is essential to consider other variables such as household and occupation.

The results obtained with a comprehensive battery of NPA instruments provides a baseline of impaired cognitive function(s), which helps to define the duration and type of neurorehabilitation that needs to be performed. For example, executive functions deficits, specifically in inhibition, planning and monitoring, demand intervention programs focused on executive functioning. Additionally, the results obtained in the memory tests contribute to personalizing and adapting CR sessions to involve the use of a calendar and notepad, warnings, teaching and training of mnemonics, face-name associations, improvement of episodic memory, semantic memory, autobiographical memory, and visual memory.

Additionally to the MoCA screening instrument, we have established the following multidimensional battery of NPA instruments to create a profile in the NeuroAIreh@b: the Clinical Dementia Rating (CDR) (32); the Subjective Memory Complaints (SMC) (32); the Free and Cued Selective Reminding Test (FCSRT) (33); the Visual Reproduction from the Wechsler Memory Scale (WMS-III) (34); the Semantic and Phonemic Verbal Fluency Tests (35); the Toulouse-Piéron test (36); the Digit Symbol Coding, the Symbol Search and the Vocabulary Subtests from the Wechsler Adult Intelligence Scale Subtests (WAIS-III) (37); the Rey-Osterrieth Complex Figure Test (38); the Adults and Older Adults Functional Assessment Inventory (IAFAI) (39) or the Patient-Reported Evaluation of Cognitive State (PRECiS) (40); the Geriatric Depression Scale-30 (GDS-30) (41) or the Beck Depression Inventory-II (BDI-II) (42); and the World Health Organization Quality of Life — Old (WHOQOL-OLD) (43) or the Quality of Life after Brain Injury (QOLIBRI) (44). This selection was made according to the following criteria: (1) NPA instruments that are standard and widely used in Portuguese clinical and research contexts; (2) adequate NPA instruments with specificity for detecting impairments in the cognitive, functional and emotional dimensions of stroke, MCI and dementia clinical populations; and (3) NPA instruments with normative data for the Portuguese population.

2.2.2 Aggregation of neuropsychological assessments

To create the ACP, we established a bridge between the different NPAs and the SDI of the patient. To the best of our knowledge, there is a gap in the literature regarding the integration of data from multiple and heterogeneous NPA instruments to create an ACP.

As stated above, in the initial phase we did not have enough data on stroke, MCI and dementia patients to use an ML approach and quantify the contribution of each NPA to the different dimensions of the profile. Therefore, we developed the following strategy: (1) A focus group of 6 neuropsychological assessment and rehabilitation experts defined a general formula for aggregating the NPAs, considering weights for the relation between NPA instruments and cognitive domains/subdomains (2) the NPA instruments were empirically aggregated, based on the expert's experience, and a first value for the weights was obtained, (3) the previous aggregation was pre-validated by using correlations obtained from patients with dementia and weights were readjusted, and (4) ML algorithms for future calibrations were defined.

2.2.3 The general formula

We propose to map NPA instrument scores to a consolidated ACP in the interval between 0 and 100, and the Equation (1) is used for the *Mapping*. Note that it is formulated owing to no data.

$$ACP_k = \sum_{i=1}^{n}\sum_{j=1}^{m} Norm(NPA_i Dom_j).W_{kij} \tag{1}$$

where, m is the number of times a Dom a NPA tool appears and n the number of NPA instruments. ACP_k is the cognitive domain k for this ACP, $NPA_i Dom_j$ is the domain/subdomain j of the NPA tool i, $Norm$ is a normalization function, which interval is ranged between 0 and 100. Finally, W_{kij} is a weight value in the interval 0 to 1, where $\sum w_{kij} = 1$. The ACP for a patient is therefore defined as

$$ACP = \ll ACP_1, \ldots, ACP_r \gg . \tag{2}$$

where r is the total number of domains/subdomains considered.

For example, if we use the weights for working memory (wm) provided on Table 1 we obtain:

$$Working\_Memory = \begin{cases} WaisIII\_DSC_{\text{wm}} * 0.6854+ \\ +MoCA\_digit_{\text{wm}} * 0.1713+ \\ +MoCA\_calculus_{\text{wm}} * 0.0857+ \\ +MoCA\_target_{\text{wm}} * 0.0576 \end{cases}$$

The ACP itself is not enough to determine the CS of a patient. To obtain it, we need to compare it with the Normative Data (ND). The ND is organized considering the SDI of the patient. If we interpret the ACP using the ND from all the NPAs considering the patient's SDI, we will get his/her CS. The next step is to solve how to contextualize this profile. We propose the following formula:

$$SCP_k = \sum_{i=1}^{n} Norm(ND_i, SDI).w_i \tag{3}$$

where n = number of NPA instruments. SCP_k is the CS for the domain/subdomain k from ND and SDI. $Norm$ is a normalization function in which the interval ranges from 0 to 100. ND_i is the profile placement in the normative data of k for each NPA tool i used to calculate ACP and SDI is patient's SDI. Finally, w_i is the

TABLE 1 Combination of the NPA instruments according to the cognitive domains and subdomains assessed.

General cognition			**MoCA total 100% (50%)**		**CDR cognitive cluster 100% (50%)**	
Orientation			**CDR orientation 33,33% (72,73%)**		**MoCA temporal and spatial orientation 12,5% (27,27%)**	
Memory	Immediate	Verbal	FCSRT immediate memory **100% (68,57%)**	CDR immediate memory **33,33% (22,86%)**		MoCA delayed recall **12,5% (8,57%)**
		Visual	FCRey 3 min **100% (50%)**	WMSIII visual reproduction immediate recall **100% (50%)**		
	Delayed	Verbal	FCSRT delayed recall **100% (75%)**		CDR memory delayed recall **33,33% (25%)**	
		Visual	WMS-III visual reproduction delayed recall **100% (50%)**		WMS-III visual reproduction recognition **100% (50%)**	
Executive functions	Working memory		WAISIII digit symbol coding **50% (68,54%)**	MoCA digit in reverse **12,5% (17,13%)**	MoCA calculus **6,25% (8,57%)**	MoCA target detection **4,2% (5,76%)**
	Processing speed		WAISIII symbol search **50% (36,36%)**	WAISIII digit symbol coding **50% (36,36%)**	Phonemic and semantic verbal fluency **33,33% (24,23%)**	MoCA phonemic verbal fluency **4,2% (3,05%)**
	Verbal fluency		Phonemic and semantic verbal fluency **33,33% (88,81%)**		MoCA phonemic verbal fluency **4,2% (11,19%)**	
	Inhibition		Phonemic and semantic verbal fluency **33,33% (79,88%)**		MoCA target detection **4,2% (10,06%)**	MoCA phonemic verbal fluency **4,2% (10,06%)**
	Visuoconstructive capacity		FCRey copy **100% (50%)**		WMSIII visual reproduction total score **100% (50%)**	
Language	Comprehension		WAIS-III vocabulary **50% (100%)**			
	Expression		MoCA naming and repetition **12,5% (100%)**			
Attention	Divided		WAIS-III symbol search **50% (100%)**			
	Sustained		Toulouse-Piéron test **100% (81,33%)**	MoCA target detection **4,2% (3,42%)**	MoCA calculus **6,25% (5,08%)**	MoCA digit direct **12,5% (10,17%)**
Premorbid intelligence			WAIS-III vocabulary **50% (100%)**			
Functionality		Basic ADLs	IAFAI basic ADLs **100% (50%)**		CDR personal care **100% (50%)**	
	Instrumental – familiar ADLs	Instrumental – familiar ADLs **100% (50%)**		CDR home and hobbies **100% (50%)**		
	Instrumental – advanced ADLs	Instrumental – advanced ADLs **100% (33,33)**		CDR community affairs **100% (33,33%)**	CDR judgment and problem solving **100% (33,33%)**	
	Cognitive deficits perceived impact		PRECiS or SMC* **100%**			
Depressive symptomatology			GDS-30 or BDI-II* **100%**			

The normalized values are presented between (). *Selection according to the patient's age.

weight value of the ND i for the domain k in the interval 0 to 1, and the $\sum w_i = 1$.

First, it is essential to mention that we do not have access to the normative values for each NPA /task/question. These data are only available for the total and, in some cases, sub-totals of each NPA. A weight needs to be given for the pair ND-SDI to have the aggregated result of all NPA instruments involved when we do the sum. This pair provides the average performance on a specific NPA for someone that belongs to the same socio-demographic group (e.g., 65–70 years old, 12 years of schooling) as the patient. Since the MoCA ND values are available for the Portuguese population (45), we will use it as an example, considering the memory domain. The result of this formula would be the average result expected for someone with a similar SDI as the patient. By doing a simple cross-multiplication between the ACP memory score and the result of this function, we can get the relative value of the patient when compared with the ND. This value would be, in this example, the memory domain in the CS of the patient, where 50th percentile represents an average performance considering the patients' socio-demographic group in the memory task.

The main challenge here is how to determine the value of weight W_{kij} in Equation (1) and the value of weight w_i in Equation (2).

2.2.4 Starting with no data

Table 1 depicts each of the NPA instruments' weight in the different cognitive domains and subdomains. As stated above, this NPA instrument aggregation resulted from a focus group session with six neuropsychological assessment and rehabilitation experts. Since most of the selected NPA instrument scores and subscores may contribute to evaluating different cognitive domains and subdomains, the NPA instrument weight was divided for the number of sub-scores it involves and the number of cognitive domains and subdomains it targets.

For example, the MoCA (100%) is a cognitive screening measure that gives us information about general cognitive functioning. Through eight of its subtests (12.5% each), such a multidimensional and comprehensive tool contributes to assessing different domains and subdomains: MoCA calculus (12.5%) contributes to the executive functions assessment in the working memory subdomain (6.25%) and attention in the sustained attention subdomain (6.25%).

For each domain to sum a total of 100%, these values were normalized. As such, if a subdomain has only one NPA tool entry with 50%, it will be normalized to 100%. If no score is given in one or more NPA instruments subdomain, the NeuroAIreh@b system will normalize the existing scores according to the non-normalized values.

These empirical values were validated in two different ways: First, we checked if the weighted sum for the aggregation of NPAs validates the basic aggregation rules [see (29), (Chapter 6)]. For the second validation, we compared it with data from other sources, namely the Alzheimer's Disease Neuroimaging Initiative database (ADNI).[1] The ADNI is a longitudinal multisite observational study of elderly individuals with normal cognition, MCI, and AD. Since it includes a battery of NPAs, we used ML techniques to find correlations between the different NPA instruments and compare them with the empirical correlations, establishing an analogy. To obtain the aggregations for Alzheimer's disease, the following procedure was adopted:

1. A file from the database containing all key tables merged into one was prepared. As an outcome, this file contains the totals from all the key tables and all the assessment results. It includes the diagnosis of each patient, filtered by the NPAs used in NeuroAIreh@.
2. The records were depurated with incomplete data, removing it from the dataset and obtaining a new dataset with around 2200 lines. To clean data sets before creating a model, we have tested the Variance threshold, Pearson Correlation and Analysis of variance.
3. The correlation between tests was checked using the following ML algorithms: Linear Regression, Logistic Regression, Decision Tree, Support Vector Machine, Naïve Bayes, K-nearest neighbors, and Random Forest. Figure 2 shows an example of the correlations obtained. For a full description, see (46). This correlation showed which NPA instruments can assess the exact domains (e.g., memory, depressive symptomatology).

Once we get enough data, we will calibrate W_{kij} in the Equation (1) and w_i in the Equation (2). For the weight computation, some statistical learning, ML or DL techniques will be applied to NPA instruments data to obtain highly optimal W in the Mapping process, such as Principal Component Analysis, random forest or neural network. Besides, if the number of *Dom* and *NPA* grows over time, the system performance may decline, and the data will suffer from high dimensionality. To overcome such problems, feature selection techniques like Principal Component Analysis, LASSO, Ridge or t-distributed Stochastic Neighbor Embedding can be used. These techniques generate highly influential parameters without losing much information.

2.3 The training challenge

The training challenge encompasses two different parts: the first one is the development of CTTs to create the CTTs repository, and the second one is the selection and personalization of CTTs given a training objective [see (5) in Figure 1].

The set of CTTs is integrated and managed by a software, the Reh@Sync (47), that is in charge of:

1. Exchanging and managing patient data related to the training sessions with the CTTs.
2. Selection of the ideal CTTs for the provided cognitive profile.
3. Difficulty adaptation during a session and in between sessions.
4. User interface (UI) for patient's interaction with his/her training sessions and CTTs.

2.3.1 The training tasks definition

To identify and select the most relevant ADL-oriented CT content to create the training tasks repository, interviews

1 http://adni.loni.usc.edu

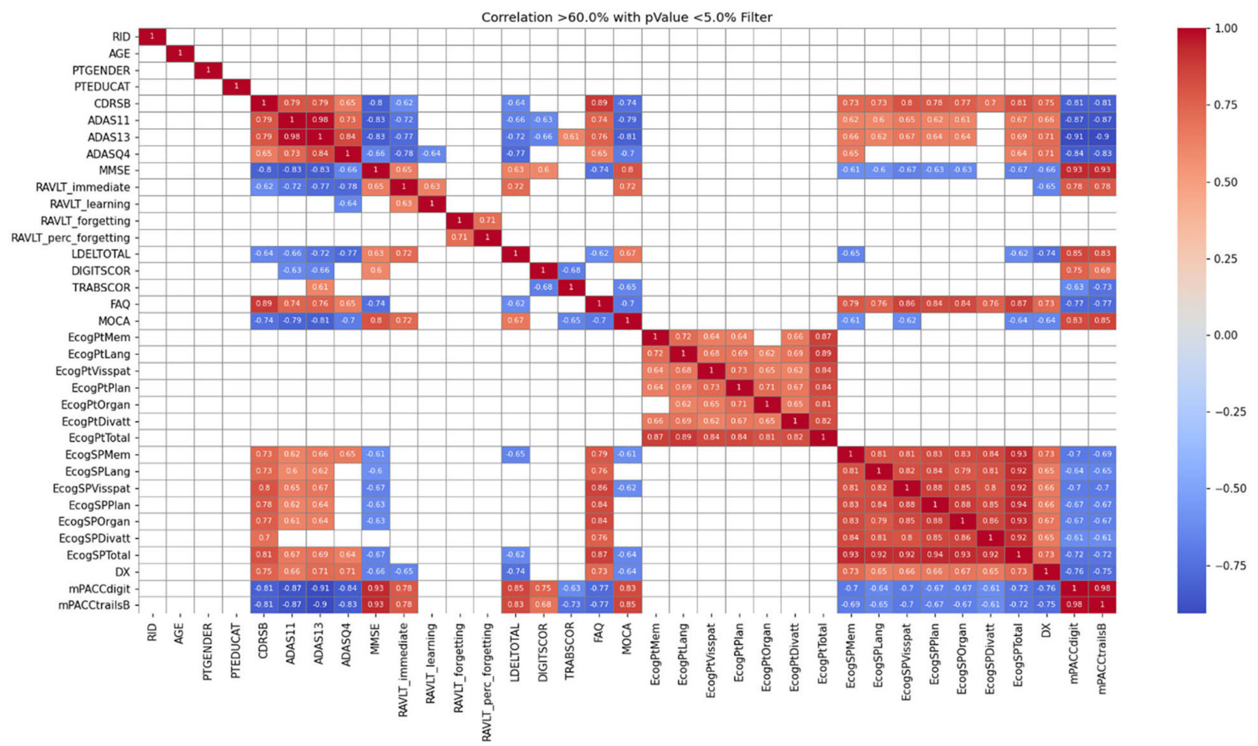

FIGURE 2
Pearson correlation in the ADNIMERGE table with filter above 60% and p-value below 5%.

were conducted with chronic stroke patients (n = 15) and neuropsychologists (n = 20).

We recruited a sample of 15 stroke participants (nine male, six female) in the community setting, with a mean age of 59.66 (SD = 11.25) and an average of 8.46 (SD = 4.73) years of formal education. Participants were administered the Adults and Older Adults Functional Assessment Inventory (IAFAI) (39), which is a self-report functional incapacity measure that includes both basic (BADL) and instrumental activities of daily living (IADL). We aimed to identify which activities of daily living participants presented impairment—independence with difficulty or dependency—due to cognitive-related factors. Impairment in activities of daily living (ADLs) due to physical or emotional-related factors was not considered. Overall, participants reported more difficulties performing household and advanced IADL, as illustrated in Table 2, due to cognitive-related factors (e.g., attention, memory, problem-solving, mental fatigue). The three most affected IADL domains were conversation and telephone (IADL - Household), comprehension and communication (IADL—Advanced), and use and home security (IADL—Advanced) (48).

Concerning the interviews with neuropsychologists, semi-structured interviews were used to inquire about 20 Portuguese professionals with expertise in assessing and rehabilitating stroke patients. These interviews had three main objectives: (a) identify the most common post-stroke cognitive and functional impairments according to their clinical practice; (b) characterize and describe which conventional and/or innovative CR approaches were typically provided following a stroke in the Portuguese clinical setting; and (c) determine guidelines for the development of ICT-based ecologically valid cognitive training interventions (e.g., content, parameters, operationalization procedure, assessment measures) designed for stroke patients. Here, we will focus specifically on objective (c) because it tackles aspects related to the content selection and implementation procedure. As such, the most relevant findings concerning the training content selection and implementation processes will be summarized below (49).

Regarding training content, neuropsychologists stated the importance of designing more ecologically valid cognitive CTTs. They agreed that this could be accomplished by incorporating IADLs' simulations within the CTTs since these activities are known to involve more significant interaction with the social contexts and higher cognitive demands compared to BADLs. In fact, the term cognitive IADLs can be used when referring to everyday or functional cognition, defined as the ability to solve cognitively complex tasks of everyday life in the real world (50). These functional activities typically have a multitasking component and, hence, involve integrating several cognitive processes being engaged simultaneously (51, 52). On that note, the three most mentioned IADLs by the neuropsychologists were meal preparation and cleanup, shopping (e.g., supermarket, restaurant, pharmacy), and financial management, followed by health management and maintenance, driving and community mobility (use of public or private transportation), home management, and functional communication. After specifying the content of the tasks, neuropsychologists were questioned about the tasks'

TABLE 2 Compromised IADL domains according to community-dwelling stroke patients ($N = 15$).

Type of IADL	IADL domain (items)	Items	Frequency (%) of patients
IADL-household	Conversation and telephone use (five items)	Transmit a message	7 (46.67%)
		Understanding what people say	3 (20%)
		Holding a conversation with someone	4 (26.67%)
	Meal preparation (two items)	Cooking a meal	2 (13.33%)
	Home security (six items)	Having contacts for emergencies	1 (6.67%)
		Remembering where important objects are (e.g., keys, documents or money)	5 (33.33%)
		Turn off the stove, oven or iron	1 (6.67%)
IADL-advanced	Comprehension and communication skills (two items)	Telling someone the main aspects of TV news	8 (53.33%)
		Reading and understanding a book or a newspaper	1 (6.67%)
	Health-relation decision making (three items)	Be careful to pick a recipe or buy medication before it runs out	2(13.33%)
		Going to a medical appointment and explaining clearly why	2(13.33%)
		Taking medications as prescribed	4 (26.67%)
	Going out and transportation use (two items)	Going out without getting lost	2 (13.33%)
		Using public transportation when needed	2 (13.33%)
	Leisure time and interpersonal relationships (two items)	Plan and organize something with family or friends	4 (26.67%)
		Continue to perform some usual activities	4 (26.67%)

operationalization procedure, i.e., for instance, how did they envision a CTT inspired by the IADL "meal preparation and cleanup" (e.g., what type of instruction would the task have, what would the task goal be)? We found that most neuropsychologists struggled to provide concrete examples regarding this issue; nonetheless, some operationalization proposals for CTTs were given according to their underlying IADL (see Table A1).

The data gathered from the semi-structured interviews were used to create a preliminary prototype of the digital CTTs using the Musiquence platform (see Figure 3). This platform was initially designed by our team for the cognitive stimulation of people with dementia, capitalizing on music and reminiscence therapy principles (53). Musiquence includes a Game Editor that allows users to develop and customize CTTs based on the users' specificities. Each slide within the Game Editor represents an activity (e.g., quiz 2.0, association, search) that can be completely customized regarding instructions, background images, and response options (53). Each CTT was developed by a psychologist who adjusted task difficulty according to her clinical judgment by manipulating several task parameters (e.g., number of target stimuli, number of distractors, length of the instruments). The CTTs were then organized according to three major themes related to IADLs: functional communication and transportation use, cooking and shopping, and financial management and health-related issues. Subsequently, we have designed a computerized CT program comprising 14 sessions, each lasting 30 min. This program was administered to chronic psychiatric inpatients instead of stroke patients due to restrictions related to the COVID-19 pandemic in accessing the stroke population. The findings of this pilot randomized controlled trial revealed promising preliminary outcomes regarding the impact of the computerized CT program on participants' cognitive and noncognitive domains (54).

2.3.2 The training tasks development process

The design process of the initial set of CTTs consisted of a series of brainstorming sessions among psychologists and developers of the NeuroAIreh@b team. These brainstorming sessions were divided into two parts:

1) First, the information gathered in Section 2.3.1 was analyzed and structured so that the different variables needed for the construction of the digital version of the CTTs were identified.

2) Second, the Braindrawing method was used to design the User Interface, which was also useful for brainstorming the CTTs mechanics (55). Four participants sketched the UI in short design rounds, exchanging the sketches between themselves at the end of each round. At the end of all rounds, results were discussed, and both the UI and the task mechanics were redesigned. Cooking was one of the most mentioned ADLs and, consequently, was the first to be implemented. This task was also used as the basis for deciding on the design and mechanics of the first set of CTTs. The cooking ADL-related tasks addressed three different types of cognitive tasks inspired in our previous work with the Reh@City (11, 12, 56): search and selection (Reh@bSearch), action-sequencing (Reh@bOrganize) and categorization (Reh@bCat) (47).

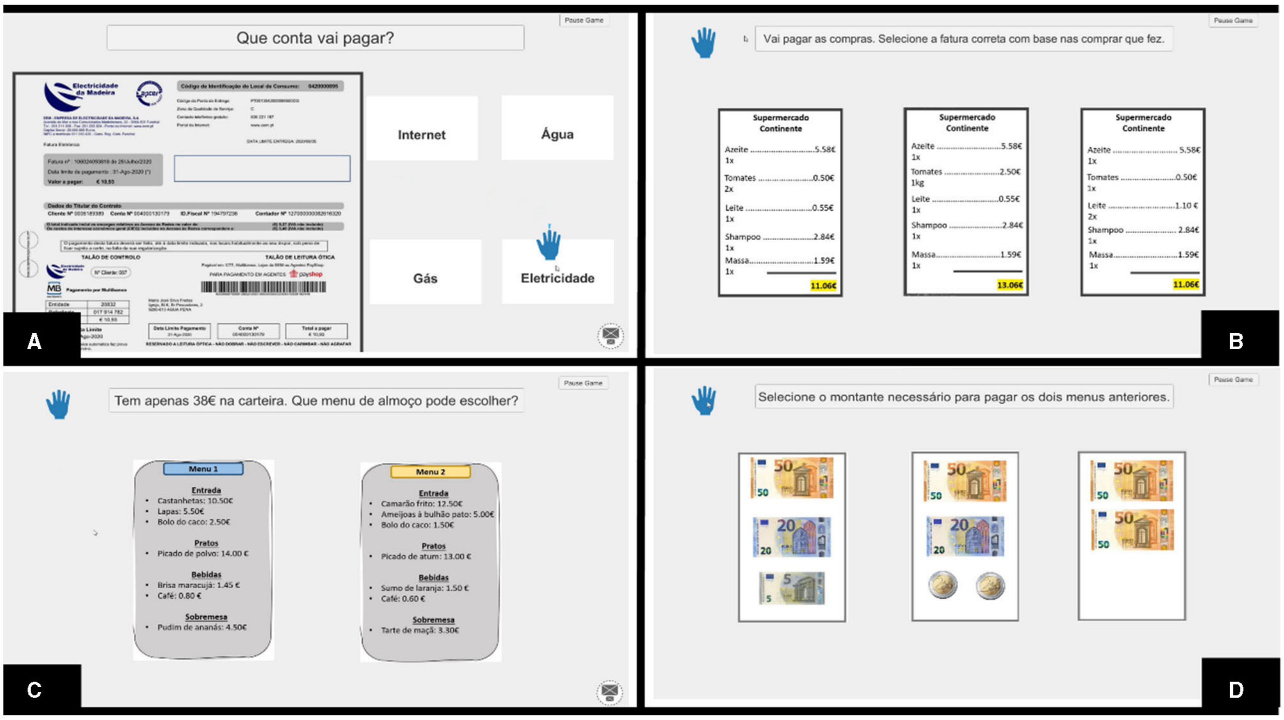

FIGURE 3
This figure represents four CTTs used in the computerized CT program: **(A)** Analyze the bill task—participants are required to analyze a specific bill (e.g., internet, electricity, gas) and to answer several questions related to that bill (e.g., What is the total cost of the bill?); **(B)** Choose the correct invoice—based on the prices of grocery items shown on a from the previous task, participants were required to select the correct invoice among incorrect invoices. To do so, they needed to retain the information regarding the prices and the number of items and then perform some calculations to estimate the total cost of their purchase; **(C)** Pay the lunch menu(s) task—participants are required to analyze several lunch menus and to select the right menu(s) considering the amount of money available; and **(D)** Pay the lunch—participants must select the correct amount of money needed to pay the previously selected lunch menu(s).

In the Reh@bSearch, which consists of a cancellation task, the patient is presented with a list (i.e., shopping list, recipe) and must select the target items (minimum 1; maximum 12) among distractors (maximum elements per section: 20; maximum number of sections: 8) within a time limit in the different sections of a scenario. Reh@bSearch allows the use of different scenarios, such as a supermarket, a kitchen, or a warehouse. The Reh@bOrganize task consists of an action-sequencing task where steps are displayed scrambled to the patient. The patient must organize them in the correct order of execution. This task supports both text and images, with a minimum of 2 and a maximum of 12 steps. In the Reh@bCat, the patient must categorize items (minimum 2; maximum 60) into the correct category container (maximum 4), which can be a fridge or a cabinet, for instance. After being correctly categorized, the item is removed, and a new item to categorize is listed. At the same time, there are yet items to categorize on a list (see Figure 4).

A selection of broad contexts to integrate different tasks was performed. For example, in everyday life, meal preparation and cleanup are commonly performed in the context of a kitchen, and shopping is commonly done in a supermarket. As such, the kitchen contextualized both meal preparation and cleanup activities, and the supermarket contextualized the shopping activity. All the described tasks target several cognitive domains, namely, attention, executive functioning, memory, and language (57). The involvement of each cognitive domain is manipulated according to the goal of the CTT (e.g., to increase memory involvement, the instruction can be removed during task performance; for higher attentional involvement, the number of items can be increased).

There is a process of feedback and reward that is followed by all the tasks, namely: (1) colors and sounds distinguish the correct/incorrect feedback; (2) for each correct action, the patient is rewarded with points and no negative scoring is given on errors; (3) when the established task time ends, the system is prepared to display hints to complete the task and the patient gets half the points; (4) the performance in each task is translated into a percentage that will inform the reward system (lower than 50%—no medal is given, 50–70%—copper medal, 70–90%—silver medal, more than 90%—gold medal).

2.3.3 The training tasks' interdependency

As previously mentioned by neuropsychologists, it is crucial that one task can be transformed into a more complex one. However, previous studies reported that an increase in complexity does not always translate into an increase in performance (58, 59). One way to simplify a complex task is to divide it into smaller steps, and if we take a close look at an ADL, it consists of a series of steps and activities. Let us consider the example of cooking. First, we need to identify the ingredients needed for a determined recipe (interpretation); then, we need to select them from the

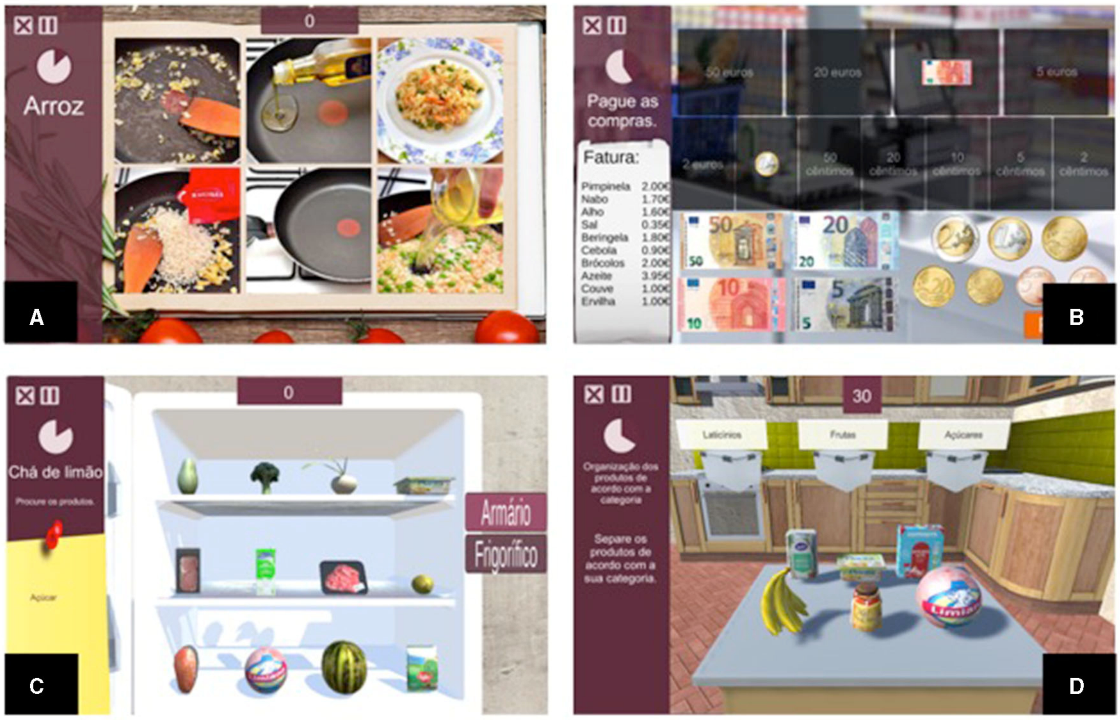

FIGURE 4
The four Reh@Apps of the NeuroAIreh@b CT platform: **(A)** Reh@Search; **(B)** Reh@Org; **(C)** Reh@Pay; and **(D)** Reh@Cat (47).

different places they can be stored in the kitchen (cancellation). Subsequently, we need to perform the needed steps to execute the recipe (action sequencing). Finally, we may need to organize the place by putting the items in their storage place (similar to a categorization task). Although this all happens in the kitchen, we may identify other related activities happening in different scenarios, such as supermarkets. To have the items to cook a specific recipe, we may need to buy them first. Therefore, we identify a specific dependency between activities and scenarios of the same context.

Previous work with the Reh@City did not consider interdependency between activities (12, 56, 57). Nonetheless, we hypothesize that it may be important to improve rehabilitation outcomes since it may increase the ecological validity of the tasks, helping in retaining and transferring decision-making and programming abilities related to complex tasks (59). Therefore, we want to implement this interdependency between the activities of the same context in the NeuroAIreh@b platform. For this, the CTTs content consists of contexts (Main ADLs) and their respective activities (Sub-ADLs) are performed through a cognitive task (for instance, cancellation, action sequencing or categorization).

Since most of the content items that are used to personalize the tasks and adapt difficulty levels are the same for different activities and scenarios, we developed the Daily Life Library (DLL), an Asset Bundle created in Unity 3D®(Unity Technologies) where all objects and scenarios, common to all CTTs, are stored. This translates into improving system performance while enabling accessibility to a library of everyday life objects for the current and future NeuroAIreh@b tasks.

2.4 Executing the training tasks

2.4.1 The training tasks selection

All the defined ADLs-based CTTs are integrated into the Reh@Sync. All CTTs are independent softwares and can receive the values of their parameters from an external source. Each CTT has its model, which gathers information on the levels of the cognitive domains/subdomains that each CTT trains. This is used by the Reh@Sync to optimize the selection of CTTs [see (5) in Figure 1] in the following way:

1. Reh@Sync receives the cognitive profile of the user, the challenge thresholds, the preferences in terms of ADLs, and the emotional profile as inputs.
2. The personalization manager iterates through all the CTTs, checks their domains' levels and matches them to the CTTs that train the most needed domains of that specific patient. Then, the system returns a list of CTTs ordered by their importance to that patient, where the ones at the top are the ones that target the domains/subdomains that the patient requires to train the most. To calculate this order, we defined a distance (which is a slight variation of Hamming distance) for each domain/subdomain in the following way:

- 0 if the value of the CS for a domain/subdomain that the patient needs to train is in the range covered by the CTT.
- *n*, where *n* is the minimal distance between the value of the CS for a domain/subdomain that the patient needs to train and the range covered by the CTT.
- 10 (the maximal distance value) if the domain/subdomain that the patient needs to train is not covered by the CTT.

3. The content of the activities is filtered by the contexts that match the patient's ADLs with more impairments and the training details (number of sessions and time per session).
4. The Reh@Sync reads each of the selected CTTs and launches it parameterized according to the patient's cognitive profile. The Reh@Sync also oversees the personalization and adaptation of the CTTs to each cognitive profile.

2.4.2 Adaptation during the training session

In our previous studies with the Reh@City (56), each participant was assigned a set of CTTs individually, personalized according to the patient's cognitive profile domains: attention, memory, executive function, and language. This profile was found through the administration of MoCA, with values being converted to a 1–10 scale, with 0.5 intervals. For instance, the maximum value that is possible to achieve on the attention domain of MoCA is 6; this result was then normalized to the Reh@City 1–10 scale, corresponding to the value of 10. The process was similar for the remaining domains: memory, executive function, and language, which can hold the maximum values of 11, 7, and 6, respectively. One additional parameter, the difficulty, was used to adjust the cognitive tasks based on the user performance. The initial value of the difficulty was found by normalizing MoCA's total score to the Reh@City scale.

Then, the intervention consisted of performing task sets. At the end of each set, the difficulty level for the following set of tasks was calculated based on the participant's performance. If the user obtained an average performance lower than 50%, the difficulty was reduced by 0.5 points; if higher than 71%, the difficulty was increased by the same amount; if performance was from 51 to 70%, the difficulty value remained the same. In the NeuroAIreh@b prototype, we implemented this same adaptation method but in a more flexible manner. As such, the neuropsychologist administering the training through NeuroAIreh@b can adjust the minimum and maximum thresholds. This helps the Reh@Sync to learn how to make decisions about when to increase, decrease, or maintain the difficulty. This translates into the following:

- The narrower the thresholds, the higher the number of fluctuations that may occur in terms of difficulty change.
- The wider the thresholds, the lower the number of expected changes in difficulty.
- The lower the maximum threshold, the more difficulty may increase.
- The higher the maximum threshold, the harder it is to have an increase in difficulty.
- The lower the minimum threshold, the more difficulty may decrease.
- The higher the minimum threshold, the harder it is to have a decrease in difficulty.

The Reh@City activities were initially personalized to a specific cognitive profile. Only one parameter, the difficulty level, would change from session to session, considering the overall mean performance of all activities together. In the Reh@Sync, we refine this information in session by evaluating each CTT performance and adjusting the difficulty level for that specific task accordingly. This allows us to tweak the difficulty of the settings to keep the patient in a state of flow (60). It has been proven that people at this level of concentration and immersion are most effective, which is expected to lead to better rehabilitation outcomes.

At the end of a training session, all the performance information is sent to the NeuroAIreh@b server, which estimates a new cognitive profile for the patient that will be sent again to the Reh@Sync, restarting the cycle of CTTs.

2.5 The profile dynamics

As we mentioned in Section 2.4.2, the training task adapts the parameters to maintain the performance between a predefined range (e.g., 50–70%). Suppose that a determined parameter of a CTT suffers an increment in its value during the training sessions. In that case, the patient manifests an improvement in his/her CS due to the rehabilitation.

The performances obtained at the end of a training session through the CTTs are used to estimate an intermediary virtual profile that will serve as input to the next session, enabling the CTTs to be adapted to the patient. However, relating the CTTs' difficulty and cognitive domains is not linear because a CTT trains multiple cognitive domains, and it can be difficult to differentiate how much of an obtained performance relates to each specific domain or subdomain.

To help establish this relationship, NeuroAIreh@b creates and maintains a correlation between the parameters of the CTT and the domains/subdomains for each CTT. With these correlations and the performances of all the CTTs in the session, the system summarizes the outcome in a sentence in the language defined in Definition 2.2. This sentence is the input for the profile update. Hence, all combinations of the different domains that could output that specific performance should be considered. By analyzing all the different combinations, we chose the model that displays the lower distance from the previous cognitive profile. The weights of the tasks (CTTs models) are used as a criterion of tiebreaker in case needed [see (24) for the theoretical method]. The new profile obtained will be the input for further training sessions; in other words, it will be used to adapt the CTTs to keep them parameterized to the ideal difficulty level over an iteration of multiple training sessions (which we will call a training program). At the end of each CT program, the patient is reassessed, and the cognitive user profile is compared to the estimated baseline profile.

This comparison will allow us to evaluate the system's performance and see if it performs as expected. The study (61) can help us to understand in which step there was a wrong prediction by the system, given the final result. Once all is done, the loop restarts until the neuropsychologist concludes that the neurorehabilitation process is completed.

3 Results

The prototype version of the NeuroAIreh@b has been through a number of clinical validation studies. Since, at the moment, there is a reduced amount of CTTs, a simplification of the NPA aggregation (depicted in Table 1) was performed (Table 3). Instead of assigning weights for each NPA, we considered the minimum and maximum raw scores that could be attained in the different performance-based NPAs. Subsequently, these scores were normalized on a scale of 1–10. Finally, we computed the mean of all the normalized scores within each subdomain to derive a normalized score representing each of the five macro-cognitive domains. This process allowed us to generate the participants' baseline neuropsychological profile, comprising the following macro-domains: general cognition, attention, memory, language and executive functions.

An initial pilot study was conducted with ten chronic stroke survivors who were enrolled in a one-month intervention with the prototype version of the NeuroAIreh@b platform (62). The intervention encompassed eight 45-min tablet-based CT sessions. Participants were required to perform four different types of CTTs that were inspired by IADLs (e.g., a cancellation task in the kitchen involving the selection of the correct ingredients necessary to prepare a given recipe, a calculation task in the supermarket consisting of selecting the coins and/or bills necessary to pay for the groceries). The CTTs were implemented using the following reh@apps: Reh@Search (cancellation), Reh@Org (action-sequencing), Reh@Pay (calculation), and Reh@Cat (categorization). In this pilot study, the psychologist was required to parameterize the CTTs manually according to the participant's performance in each iteration, thus modulating task difficulty considering her clinical judgment. Each participant performed each type of CTT for about 11 min. Post-NPAs were conducted to assess the intervention's short-term efficacy. Thus, at post-intervention, there were significant improvements in general cognition, as measured by the MoCA, and in functional abilities, as assessed by the IAFAI. The results from this pilot study suggested that tablet-based CT using the NeuroAIreh@b can lead to immediate short-term benefits in chronic stroke survivors' cognitive functioning and functional abilities. Furthermore, we observed a generalization of training gains to ADLs, potentially attributed to the greater ecological validity of the training content. Importantly, the performance data obtained from this pilot study were used to develop a difficulty progression algorithm to optimize training personalization and adaptation based on participants' neuropsychological profiles and task iterations.

Moreover, a five-week blended neurorehabilitation intervention was conducted with four community-dwelling stroke survivors to evaluate its feasibility, acceptability and preliminary efficacy. The intervention consisted of a total of 15 sessions, delivered between two to three times a week. This program comprised four 90-min in-person sessions, focusing on psychoeducation and compensatory strategies training, and eleven 30-min remote sessions consisting of tablet-based CT with the NeuroAIreh@b platform. Regarding the latter sessions, an additional CTT was incorporated into the platform, specifically designed to target alternating attention. This CTT was implemented through the Reh@Drive app and consisted of driving a car while avoiding road obstacles and collecting gasoline bins. To evaluate the short and long-term impact of the program, a comprehensive neuropsychological assessment was conducted at three different moments: baseline, post-intervention and three-month follow-up.

Firstly, regarding the feasibility of the blended neurorehabilitation program, all participants successfully attended the in-person sessions and completed the prescribed remote sessions, with only minor technical issues (12.5% of technical problems). Consequently, the high training compliance rate highlights the feasibility of the intervention. Secondly, in terms of acceptability, participants reported high levels of satisfaction following the intervention, indicating that the program was meaningful at a cognitive and emotional level. Finally, efficacy-wise, participants demonstrated reliable, differential improvements in several neuropsychological assessment measures immediately after the intervention, some of which were maintained at three-month follow-ups. Furthermore, reliable declines were also observed in two participants, more specifically in processing speed, semantic verbal fluency and visual memory. In addition, no differences were observed concerning participants' changes in goal attainment at post-intervention compared to the baseline. Nonetheless, differences emerged during the three-month follow-up; two participants reported successfully attaining all their rehabilitation goals. On the other hand, only one participant could not achieve any rehabilitation goal.

Overall, our findings provide evidence supporting the feasibility, acceptability and preliminary efficacy of the blended neurorehabilitation. To further validate the tablet-based CT framework (NeuroAIreh@b), we plan to conduct a randomized controlled trial with a larger sample of stroke survivors (63).

4 Discussion

Over the last few years, AI techniques have been widely applied in healthcare, raising the discussion of whether, in the future, they would replace health professionals. From our perspective, AI techniques have the potential to complement and enhance the work of health professionals by assisting them in optimizing clinical diagnosis, treatment decision-making and data analysis (64). The ability to learn, self-correct and update the knowledge based on feedback are important AI features that improve its accurateness, thereby reducing assessment and rehabilitation errors that may occur in clinical practice (65). As mentioned above, cognitive deficits rehabilitation is a quite complex process with a series of clinical decisions based on empirical knowledge that would largely benefit from these AI techniques features as a supportive tool.

This work aims to contribute to the advancement of the scientific literature in the area of AI techniques (such as ML and belief revision) applied to the neurorehabilitation of people with cognitive deficits. We believe that the complementarity between AI

TABLE 3 Cognitive profiling reformulation and simplification.

General cognition (Min-max = 0–10)			**MoCA – Total score (Min-max: 0–30)**	
Memory **(Min-max=0-10)**	Immediate	Verbal	FCSRT – Total immediate memory **(Min-max: 0–48)**	
		Visual	ROCFT – 3-minute immediate recall trial **(Min-max: 0–36)**	
	Delayed	Verbal	FCSRT – Total delayed recall **(Min-max: 0–16)**	
		Visual	NA for this study	
Executive functions **(Min-max = 0–10)**	Working memory		Digit symbol coding (WAIS III) **(Min-max: 0–133)**	
	Processing speed		Symbol search (WAIS III) **(Min-max: 0–60)**	Digit symbol coding WAIS III **(0–133)**
	Verbal initiative		Phonemic verbal fluency test **(Min-max: 0–57)**	Semantic verbal fluency test **(Min-max: 0–27)**
	Inhibition		Phonemic verbal fluency test **(Min-max: 0–57)**	Semantic verbal fluency test **(Min-max: 0–27)**
	Visuoconstructive capacity		ROCFT – Copy trial **(Min-max: 0–36)**	
Language **(Min-max = 0–10)**	Expression		Phonemic verbal fluency test **(Min-max: 0–57)**	Semantic verbal fluency test **(Min-max: 0–27)**
	Comprehension		Vocabulary (WAIS-III) **(Min-max: 0-66)**	
Attention **(Min-max = 0–10)**	Divided		Symbol search (WAIS-III) **(Min-max: 0–60)**	
	Sustained		Toulouse-Piéron test – Total score **(Min-max: 0–37.5)**	
Premorbid intelligence **(Min-max = 0–10)**		NA for this study		

and neuropsychology creates a virtuous circle advancing both fields' objectives in such an important area as neurorehabilitation. As such, our ultimate goals are 2-fold: (1) provide neuropsychologists with an innovative paradigm to support the clinical decisions in prescribing CT sessions for people affected by cognitive deficits, the NeuroAIreh@b and (2) contribute to a worldwide effort aiming at using AI techniques to improve the management of cognitive deficits associated to stroke, other acquired brain injuries and degenerative disorders (66).

The fact that the NeuroAIreh@b CT tasks are being implemented in VR-based ADLs simulations provides greater ecological validity to the CT (10, 12). Although there is no strong evidence that the use of VR is more beneficial than conventional therapy in cognitive deficits rehabilitation, this technological approach has been demonstrated to be beneficial as complementary to usual care for different reasons: it is more engaging, enables a more intensive training, provides immediate feedback and tasks have greater verisimilitude and validity (7). We believe that the operationalization in VR according to the interviewed patients and neuropsychologists' requirements, will have a positive impact on CT efficacy and transference to everyday-life activities performance, which is the major goal of neurorehabilitation (5).

The NeuroAIreh@b entails an ML component for managing NPA data, which is represented by the ACP, to adapt and personalize the intervention to the patient CP. Although the first CP is made according to the NPA static scores, according to our experts' NPAs aggregation, session-to-session performance in the NeuroAIreh@b CTTs is used by the system to update the profile dynamically. For instance, the patient starts with 7/10 in Memory, but if he/she outperforms, the profile is changed to 7.5/10. The accurate adaptation of the training challenge to the patient performance, together with the use of ecologically valid content, are key elements to enhance engagement, optimize learning, and address specific cognitive deficits more effectively. This has been partially (in our pilot study, adaptation and personalization were manually performed by the psychologist) corroborated by our pilot study, where we concluded that CT with the NeuroAIreh@b platform appears to be beneficial in the chronic phase of stroke, leading to gains in general cognition (MoCA) and functional abilities (IAFAI). These preliminary findings with the prototype version of the NeuroAIreh@b platform were encouraging and suggest the generalization of training gains to the patient's everyday life, which is our main goal and makes our work unique (62).

To strengthen our conclusions and collect data to validate the specific ML algorithms to calibrate the system for profile dynamics, we are performing a randomized controlled trial with stroke patients, which has been approved by the health committees of the involved healthcare institutions (Clinical Trials registration reference: NCT05929287). The intervention with NeuroAIreh@b involves twelve sessions of 30 min during a month. There are two control groups: one performs a paper-and-pencil intervention with the TG (https://neurorehabilitation.github.io/TaskGenerator/), and one is from the waiting list. All participants undergo a baseline NPA to build the initial cognitive profile - the ACP. At the end of the intervention, all participants are re-assessed to measure improvements in the NPA instruments scores. NPA results, together with the data on NeuroAIreh@b and TG performance, will be used to provide real-data evidence to prove the reliability and robustness of the described methodology and models. To verify the maintenance of potential cognitive and functional improvements, participants are submitted to a follow-up assessment at 3 and 6 months post-intervention. Additionally, as we foresee contingencies in accessing large samples of patients, we are already conducting a feasibility study at home. In this study, patients perform a pre and post-neuropsychological assessment at the hospital, but the training sessions are performed at home. This procedure enables the inclusion of participants who do not have the availability or possibility to go to the clinic several times a week. The 10 participants who finished the intervention only reported minor issues and completed the training successfully. After finishing data collection, we will establish partnerships with other Portuguese hospitals and clinics to enable a more significant number of participants.

5 Limitations

Since this work refers to presenting a methodology that has not been completely validated with an RCT, there are important limitations to be acknowledged. First, there is the fact that we are starting with no data, and the ACP algorithms are only learned through reasoning by analogy from similar existing work with the ADNI database. Using algorithms that are based on Alzheimer's Disease patients' data might not apply equally to all persons with cognitive disorders. For instance, it is expected that the evolution of the CS of acquired brain injury patients (namely, stroke and acquired brain injury) is different from the degenerative disorder patients (namely, Alzheimer's Disease). For the ACP to be updated during an intervention, the AI system needs to learn with data from patients' performance in undergoing future clinical RCTs. The pending verification/validation of the specific ML algorithms to calibrate the system for profile dynamics, which depends on collecting a considerable amount of data, is one of the limitations of our present work and one of the main challenges we face in our future work. Second, we use the MoCA subtests to account for specific domains of cognition in the NPA instruments aggregation to create the ACP. Since the MoCA is a screening tool and does not comprehensively assess specific cognitive domains, we may lack precision in our approach, especially in the cognitive domains that mainly rely on MoCA subdomain assessment results. Third, in this phase, the conceptualization and selection of the cognitive domains that are trained with each CTT are assumed and selected based on experts' opinions and experience and are still not empirically validated. Due to this inherent growing complexity of underlying models and algorithms in this methodology, AI appears here as a "black box" because the internal learning processes, as well as the resulting models, will not be entirely comprehensible (67). In other words, as we collect more data, we may not be able to understand what the cognitive constructs involved in each CTT are and how they are selected to match each ACP. Fourth, we make assumptions on what needs to be prioritized with regard to the CTTs to be selected based on numeric data from the ACP, that is, by its turn, based on our NPA aggregation (an implicitly made relationship between different types of cognitive functions and different levels of test results and their interaction). Additionally, we propose specific CTTs and implicitly assume an inherent cognitive profile. Again, in this phase, we cannot warrant that this approach is more clinically effective than any other that could be used here. The NeuroAIReh@b methodology still needs to be validated, and then, as future work, we could compare it with a different personalization and adaptation approach.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by Comissão de Ética do Serviço de Saúde da Região Autónoma da Madeira, Comissão de Ética da Casa de Saúde Câmara Pestana, and Comissão de Ética do Centro Hospitalar e Universitário de Coimbra. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

AF: Methodology, Supervision, Writing – original draft, Writing – review & editing, Conceptualization, Validation. YA: Conceptualization, Formal analysis, Methodology, Writing – original draft. DB: Software, Investigation, Writing – original draft. JC: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Investigation. MC: Supervision, Conceptualization, Writing – review & editing. LF: Software, Conceptualization, Writing – original draft. AM: Validation, Writing – original draft. TP: Software, Writing – original draft, Conceptualization, Formal analysis, Investigation, Methodology. PR: Data curation, Formal analysis, Writing – original draft. MSp: Investigation, Validation, Writing – original draft. MV: Conceptualization, Supervision, Writing – review & editing. SB: Conceptualization, Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing. MSi: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. EF: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor, TP is currently organizing a Research Topic with the author AF.

The authors declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fneur.2023.1258323/full#supplementary-material

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Design recommendations for XR-based motor rehabilitation exergames at home

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Introduction: Acquired brain injuries pose significant societal and individual challenges worldwide. The adoption of XR technologies presents an opportunity to enhance current rehabilitation procedures. However, a comprehensive understanding of the specific requirements of different user groups in XR-based rehabilitation remains incomplete. Our objective was to identify design recommendations for designers and researchers of XR-based exergames for motor rehabilitation for lower-limb motor recovery at home.

Methods: After initially conducting a mini-literature review and brief market analysis, we used a human-centered design process, interviewing central stakeholders to understand their perspectives and using thematic analysis to identify recurring themes and insights related to XR-based rehabilitation.

Results: The resulting eight key themes for integrating XR-based exergames into acquired brain injuries (ABI) rehabilitation were safety, flexibility, efficacy, usability, technology, motivation, ownership, and social factors.

Conclusion: By addressing technical and user-oriented demands, our resulting design recommendations aid designers in developing meaningful XR-based rehabilitation exercises.

KEYWORDS

motor rehabilitation, acquired brain injuries (ABI), game design, co-design, exergame, extended reality (XR), virtual reality (VR), design recommendations

Introduction

Rapid developments in entertainment technologies have made immersive gaming based on extended reality (XR) increasingly accessible and enjoyable for the general public. However, these technologies also present huge opportunities for other domains, such as medical rehabilitation. In the field of rehabilitation, an increasing number of people suffer from acute brain injuries, which pose individual and societal challenges associated with support and treatment. Consequently, there is a strong demand for novel technological solutions. Integrating the widely available XR-based technologies in rehabilitation processes has the potential to facilitate and promote it. However, the individual requirements on XR-based technologies of all involved user groups still need to be better understood and, therefore, need closer examination. Thus, this article explores those individual requirements for developing user-centric XR-exergames in motor rehabilitation.

Injuries to the brain can result in various long-lasting disabilities due to the organ's complexity. Those disabilities range from indiscernible symptoms, as the brain can compensate for some damage, to a combination of movement, sensory, emotional, and cognitive disabilities (Castor and El Massioui, 2018). Consequently, individuals affected by brain injuries often face significant difficulties performing daily activities independently and may experience social isolation (Demakis, 2007).

Acquired brain injuries (ABIs), including strokes and traumatic brain injuries (TBIs), are prevalent conditions, with a combined 81 million cases occurring each year (Dewan et al., 2018; Lindsay et al., 2019). Besides the individual tragedy ABIs cause, the economic burden on society for TBIs alone is estimated to be US$ 400 billion (as of 2017) globally (Maas et al., 2017), underlining the importance of more cost-effective rehabilitation procedures in the future.

Although stroke and TBIs differ in pathology and population, they share similarities regarding the resulting neurologic disorders and the subsequent rehabilitation procedure. Mainly the injury's size, location, and severity are determinants of the experienced disabilities (Castor and El Massioui, 2018).

In summary, ABIs are a common and complex pathology with grave consequences for a single individual and a considerable socio-economic impact. Thus, the therapy process for ABI patients to restore lost functionality and reintegrate them into society is of high priority. However, this process is complicated due to the inherent complexity and pathology of the brain.

Central to the therapy of ABIs is the brain's inherent capability to adapt and reorganize to compensate for some structural damages and regain lost functions. This process is also known as neuroplasticity. In the best case, neuroplastic processes can lead to a spontaneous recovery after an injury (Hatem et al., 2016). Nevertheless, this process requires external assistance and guidance to rehabilitate from related disabilities sufficiently. In traditional rehabilitation, the direct interaction between therapist and patient is indispensable throughout all rehabilitation phases. Despite its importance, this approach becomes economically impracticable with growing patient numbers and a decreasing healthcare workforce. Consequently, there is an ongoing effort to develop novel technologies to relieve therapists and improve the rehabilitation process. However, most research in motor rehabilitation focuses on improving upper limb functionality, and younger age groups with unique needs, capabilities, and interests are often overlooked (Rudberg et al., 2020; Holloway et al., 2022).

Only a few days after receiving ABI, the patient usually starts with intensive rehabilitation at a hospital or other medical facilities for several weeks. The patient is cared for there by a multidisciplinary team of medical professionals (Turner-Stokes, Sykes, and Silber, 2008). Physiotherapists and occupational therapists play a crucial role in the rehabilitation of motor and sensory impairments. Physiotherapists treat fundamental disabilities of movement, balance, and coordination, whereas occupational therapists assist in relearning higher-level task-specific functions (Govender and Kalra, 2007; Studer, 2007).

After regaining basic abilities, the patient is moved to outpatient units to provide regular supervised therapy while living at home. The training is transferred to the patient's home, where the patients themself are responsible for following the advised training regime (Cullen et al., 2007; Young and Forster, 2007; Maas et al., 2017). The recovery often stagnates during the later stages of the rehabilitation process (sequela stage). Additionally, the training intensity usually decreases as prolonged, frequent supervised training is not economically viable. Besides the absence of motivational support, the patient receives less corrective feedback in this phase, leading to maladaptive neuroplastic changes and potentially reversing previous improvements (Maas et al., 2017).

Exergames in physical rehabilitation are a type of serious game that aims to facilitate motor rehabilitation through physical play, other than pure entertainment. Over the last few years, they have become a valuable tool for rehabilitation, as the automatization of the training relieves healthcare providers and facilitates home rehabilitation. Those games can guide a training exercise for motor rehabilitation and sometimes give feedback on execution quality (Rüth et al., 2023). To do so, the game input must reliably track the patients' movements and consider the user's specific needs and goals. Standard tracking devices are camera systems, balance boards (e.g., Wii fit), and accelerometers (e.g., VR headset and controller) (Gómez-Portes et al., 2021; Rüth et al., 2023).

Ongoing research investigates various technologies that can supplement or improve the current rehabilitation process. Especially promising are extended reality (XR) systems, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR), due to their improved usability, accessibility, and ubiquitousness over the last few years. With the help of a head-mounted device (HMD), the users of such systems can run various applications that allow for the experience of a fully immersive virtual world environment. Sensors integrated into the HMD track the user's head movement and can be supplemented with additional controllers, body trackers, headphones, or other feedback devices (Mathew and Pillai, 2020).

In this study, we aimed to discover how XR-based exergames can be employed for motor rehabilitation and how this can be sustainably incorporated into the rehabilitation ecosystem. This was done using human-centered design (HCD) approaches and methods to uncover the target user's needs and requirements associated with motor rehabilitation using co-creation. Besides incorporating current research findings on XR-based exergaming for motor rehabilitation and commercial solutions, we interviewed stakeholders, such as subject matter experts, healthcare professionals, and patients. Based on the various knowledge streams, we developed design recommendations that can assist Human-Computer Interaction designers in understanding the respective stakeholders' needs and in developing future XR-based lower limb rehabilitation applications with a particular focus on in-home treatment.

The article is organized as follows: First, we summarize the results of a brief review of the current state-of-the-art XR-based rehabilitation technology. Next, we present findings and resulting themes from interviews with subject matter experts, therapists, and ABI patients. These findings are presented as a general patient journey and exemplified through a specific patient scenario. We then discuss our findings and present design recommendations before concluding the article.

Materials and methods

Mini-literature review on XR-based rehabilitation technologies

As the first step in this study, we researched existing knowledge on XR-based rehabilitation technologies and frameworks gained through an explorative literature review (Adams et al., 2007) and market analysis. This allowed us to understand and frame the problem using different viewpoints.

A mini-literature review was undertaken, accessing the databases of Google Scholar, PubMed, and Elsevier were searched with the search query in February 2021:

> "Extended reality (all denominations) AND (* brain injury OR stroke) AND rehabilitat* AND (exergam* OR *reality OR serious gam*) AND rehabilitation AND lower limb OR (lower limb OR balance OR posture OR gait) AND home AND (rehabilitat* OR train* OR exergam* OR * reality)."

Further, only peer-reviewed English articles published after 2004 were included. For articles related to general rehabilitation, no time threshold was set. Relevant additional literature found during extraction was added, too. After scanning the abstracts, evaluating the full article, removing duplicates, scoping, and systematic reviews, the final selection amounted to 25 publications. We identified four reoccurring themes across the literature—efficacy, motivation, ownership, and technology—and used those to structure the brief review presented below.

Interviews with subject matter experts, therapists, and patients

As part of the study to discover how XR-based exergames can play a part in home rehabilitation for lower limb function and how this can be incorporated into the rehabilitation ecosystem, we interviewed Subject Matter Experts, therapists, and patients. This way, we could identify gaps and differences in the parties' perceived realities. The questions for patients aimed to capture descriptive experience instead of normative recitals. This approach came with a preconceived motive to obtain emotional responses to challenge perceptions from the therapist interviews. For example, therapists made claims that sometimes contradicted the patients' experiences. At the same time, the questions sought to uncover experiences with logistical and systemic factors, such as specific interactions with healthcare institutions.

Interviewers

The interviews and subsequent data analysis were carried out by two authors, who were in their final year of graduate studies in industrial design engineering at the Norwegian University of Science and Technology. They received supervision from the other two authors, one of whom was pursuing a Ph.D. in medical technology with a specialization in neurorehabilitation, while the other was an associate professor in design with a focus on human-computer interaction and industrial design.

Interviews with subject matter experts

We separately interviewed three Subject Matter Experts (SME) about the challenges of ABI rehabilitation. One of the interviewees was a researcher in motor rehabilitation post-stroke and a practicing physiotherapist, and two were researchers in exergames for motor rehabilitation and former physiotherapists. All three SMEs had an average research experience in motor rehabilitation and exergaming of 8 years (SD: 3.5 years).

The physiotherapist was interviewed about 1) how to interact with patients, 2) how to measure rehabilitation progress, 3) how home rehabilitation works, and 4) their thoughts about XR in rehabilitation.

The two experts on exergames were interviewed about different topics related to exergames, such as 1) exergames used in rehabilitation, 2) XR used in rehabilitation, 3) how to test exergame prototypes with patients, 4) how to measure progression, and 5) how to design for motivation.

Interviews with therapists

The themes we identified during the literature analysis and interviews with the SMEs formed the basis for creating interview guides for both patients and therapists. These guides helped us explore these themes in depth and gather insights from those involved in rehabilitation.

Three female and two male therapists, who were recruited via rehabilitation centers, were interviewed. Two were occupational therapists, and three were physiotherapists. They had an average experience of 18 years (SD: 8.4 years) working in their fields.

The purpose of the interviews was to get a foundational understanding of how therapists work with patients with ABIs. Form and frequency of feedback and follow-up, goal setting, and communication were the focus of our probes. We were also curious about the challenges therapists encounter in handling logistical and technological aspects of their work. Lastly, the therapists spoke of their experiences and thoughts on XR and exergames and if they were familiar with the related concepts and practices.

Interviews with ABI patients

The themes from the therapist interviews informed our subsequent patient interviews. Our goal during patient interviews was to gain insights into the individuals' personal experiences and pathways.

We interviewed three male ABI patients. The average time passed since injury was 14 months (SD: 3.9 months), and they were all in their 50 s or 60 s. Two of them were from the same facilities as the therapists, recruited with the help of their care personnel. One ABI patient reached out through an open post published on Facebook. All participants taking part in the study were living in Norway. They had all received an information letter about the details of the study before recruitment. A summary of interview themes and subjects was sent to the patients beforehand for preparation, expanding on information from the initial information letter.

As ABI patients' cognitive capacity and capability can be limited, the interviews had to be adapted to avoid unnecessary strain. Therefore, an upper time limit of 30 min was set following the advice of therapists.

TABLE 1 Comparison of commercially available XR exergames for motor rehabilitation, considering the three lenses of innovation (IDEO, 2015). *-marked products were still operational during the time of the market analysis (June 2021) but are not anymore as of now.

Characteristic	Immersive rehab	Cognivive*	Neuro rehab VR	Rewellio*	Real system
Target users	Stroke	Stroke	Stroke & TBI	Stroke	Stroke
Hardware type	Commercial	Unknown	Specialized	Commercial	Specialized
Training target	Upper limb and balance	Upper limb	Upper and lower limb	Upper limb	Upper limb
Supervision	Unknown	Home (with supervision)	Clinic	Home	Clinic
Desirability	Development phase	Focused on exploration and fun	Repetitive game design	Focused mainly on therapeutic goals	Large sets of games, childish environment
Feasibility	End users are involved in the development	The hedonistic design might increase patient engagement	Prioritizes interaction with medical hardware	Good patient/therapist/ game interaction	Requires supervision due to extensive features

The patients were interviewed about 1) their injury, 2) rehabilitation details, 3) rehabilitation motivation and challenges, and 4) their thoughts about using technology and XR in rehabilitation.

Research ethics, data protection, and analysis

The study was approved by the Sikt—Norwegian Agency for Shared Services in Education and Research (reference number: 250396) and adhered to the declaration of Helsinki. The participants were informed they could refrain from the study without any consequences. Due to the ongoing COVID-19 pandemic, all the interviews were conducted and recorded in Microsoft Teams, then transcribed and summarized in short-form notes.

The pandemic also constraint the number of included study participants, due to the high evaluation cost, considering the targeted interview groups. Although their number might seem too low to obtain relevant statistical power, based on the mathematical model of Nielsen and Landauer (1993), their number suffices for heuristic evaluation at the given costs.

After conducting the interviews, the following steps were to transfer the recordings to a secure server (NTNU NICE-1) and transcribe them into text for further processing using NVivo. Here, we applied affinity mapping. We performed a comprehensive thematic analysis following the six-step data analysis process model by (Braun and Clarke, 2012): familiarization, coding, generating themes, reviewing themes, defining and naming themes, and writing up. We familiarized ourselves with the interview data through individual readings. We systematically coded key insights from these interviews in NVivo, marking each interview cue. The initial identification and subsequent reviewing of themes was a collaborative effort within the research team, with the aid of digital tools like Miro, as well as physical whiteboards and sticky notes to facilitate the process. We iterated on the clusters to arrive at meaningful, bounded themes, finally naming them at the point where they appeared mutually exclusive. Final theme names were then used to structure our design recommendations.

It is important to note that our approach to analysis differed between the literature review and SME interviews on the one hand and therapist and patient interviews on the other. The first two informed and structured our research, while the latter constituted the primary data collection and thematic analysis phase.

Results

Brief market analysis

At the time of the data collection (June 2021), the commercial XR-based rehabilitation tools listed in Table 1 were available. This shows that the market has reacted to the availability of XR technologies. Still, as two of the five products have already ceased, the difficulty of providing a functioning and desirable product is underlined. We further gave an overview on their respectively targeted patient group (stroke: 5 out 5, TBI:1 out of 5), whether the XR hardware used was commercially available (2 out of 5) or specially built (2 out of 5) for the application if any supervision is needed and the product thus more applicable for clinical applications (2 out of 5), how the delivery of training is designed, what the feasibility, how the feasibility can be assessed and its viability for home use. That information was based on the manufacturer's publications.

Resulting themes of the brief literature review

Efficacy

Naturally, the efficacy of new rehabilitation technologies in facilitating the rehabilitation process is highly prioritized. Either as part of conventional therapy or as a standalone therapy for a part of the treatment, it is shown by various studies that XR exergames can improve motor function and aid in executive skill transfer (Thornton et al., 2005; Broeren et al., 2008; Barcala et al., 2013; Levac and Miller, 2013; Lohse et al., 2013; Choi et al., 2014; Morone et al., 2014; Darekar et al., 2015; Song and Cho Park, 2015; Sekhavat and Namani, 2018; Levac et al., 2019; Maggio et al., 2019). However, there is currently insufficient evidence that XR-exergame therapy is superior to conventional treatment.

Motivation

The patients' motivation to perform a particular treatment is integral to successful rehabilitation (Egglestone et al., 2009; Lange et al., 2012; Lohse et al., 2013; Choi et al., 2014; Nijenhuis et al., 2015). As exergames are highly motivating, they have been applied extensively in similar domains (Lohse et al., 2013). Transferred onto XR exergames, their inherently motivational gaming aspect increases the patient's motivation (Lohse et al., 2013; Llorens et al., 2015).

Measuring motivations is done differently in literature, either quantitative, based on surveys, or qualitative, based on statements and themes from interview sessions (Lohse et al., 2013; Nijenhuis et al., 2015).

Besides the patients' individual needs based on the pathology of their ABI, personal preferences, skills, and goals must be considered to motivate them optimally during exergaming. Subramanian et al. (2019) have shown that different age groups respond differently to motivation factors in exergames. Nevertheless, even within the various age groups, differences must be expected and addressed individually (W. Chen, 2020).

Ownership

For XR exergame treatments, supervision by physiotherapists and occupational therapists is still considered necessary. They facilitate the XR training, provide safety during training, and motivate the patient to perform the exercises correctly (Levac and Miller, 2013; Pirovano et al., 2013; O'Neil et al., 2018; Weber et al., 2020).

As for motivational factors, the patient's individual medical and personal needs must be considered to give the users ownership. However, in research, the exergame training and the study participants are kept homogenous to allow for comparable results. This, however, does not mirror reality.

Frequent adjustment of game parameters and highly individualized games are essential to provide optimal training for various pathologies and adapt to functional improvements throughout rehabilitation.

Technology

Exergame applications are being more widely adopted due to the growing accessibility, user-friendly interfaces, and affordability of commercial XR systems. However, most studies investigating the usability of clinical VR applications focus on non-immersive technologies, like 2D screens, and only a few studies considered head-mounted immersive XR technologies (Tuena et al., 2020). Generally, exergames are effective in enhancing motor outcomes for clinical and home-based motor rehabilitation (Norouzi-Gheidari et al., 2020; Jonsdottir et al., 2021; J. Chen et al., 2022). However, little data is available regarding head-mounted XR applications (Mekbib et al., 2020; Trombetta et al., 2017; J. Chen et al., 2022).

Besides the inherent motivational aspect of gaming, the game and its hardware's usability determine its adherence. Difficulties in using XR exergames can lead to aggravation, resignation, failure to complete tasks, and adverse physical and psychological effects (Broeren et al., 2008; Larson, 2011; Levac and Miller, 2013).

Therefore, setup, onboarding, safety, usability, and time management must be considered in future studies. The actual feasibility of a therapy system can be validated for real-world environments and applications.

Resulting themes of stakeholder interviews on XR-based rehabilitation

During the thematic analysis of the stakeholder interviews, several themes related to XR-based exergames for ABI rehabilitation emerged. These are presented below. Quotes from interviewees were translated by the authors from Norwegian to English.

Safety

In most interviews, safety was discussed as a prerequisite for rehabilitation activities. In traditional therapy sessions, a supervising therapist intervenes and manually corrects rehabilitation activities for the safety of patients. However, the ability to perform exercises without supervision was deemed critical by SME1, as it helps patients transition from inpatient to outpatient and further recovery stages. SME1 also noted that game designers frequently overlook the limitations of many ABI patients. According to therapists, seemingly simple actions and movements can be risky during the early phases of rehabilitation. Unmonitored exercises are only a viable option once a certain baseline is reached. Both therapists and SME 1 emphasized the importance of games that promote safe exercise, which can help patients maintain steady progress at home. In addition, therapists highlighted the significance of workload management in ensuring safety.

Although therapists provide patients with detailed exercise plans adjusted to their needs and capabilities, they are only sometimes followed. This became clear during the interviews with patients. All the patients admitted to having been overconfident in their abilities at some point. Two patients experienced burnout due to poor workload management; one suffered a significant injury while performing a movement. Safety from physical damage due to falls was a concern of the parties interviewed, and the mental struggles overwhelming training exercises can cause were mentioned.

Flexibility

SME2 was involved in research about the parameters of gameplay and its influence on the quality of training. The presence of a feedback loop to adjust the parameters was considered necessary. This was nothing new for the therapists: Monitoring, instructing, and correcting the patients while they trained was a natural part of the therapist's feedback loop. SME2 said emerging technologies—machine learning paired with new and better sensor technology—could automatically provide this feedback loop without a therapist's supervision. However, SME2 reported, as it currently stands, that this technology seemed overly complex in terms of implementation on a user-friendly, commercially viable platform.

They implied that translating this practice into exclusively technological feedback loops would be difficult. Today, they reported, a mixture of qualitative and quantitative measures is used in rehabilitation centers to evaluate execution and progress in real-time and subsequently adapt the training. They often utilize *ad hoc* methods, such as mirrors and bathroom scales, if they find them suitable for the patient. These methods are highly interactive and create a mutual understanding of the state of rehabilitation.

Nevertheless, they also acknowledged the extensive selection of commercially available games that can supplement the rehabilitation process, even though these games are primarily designed for entertainment rather than rehabilitation purposes.

Efficacy

To ensure successful rehabilitation, it is crucial to recognize that effects and outcomes are highly individualized, as mentioned by SME Physio. He and the therapists further stated that it is essential to craft roadmaps for patients using qualitative and quantitative measurements that can be compared to an indisputable baseline. This is important, not just during the early phases but throughout the whole rehabilitation process. One of the patients also agreed on that point.

SME2 and the therapists said that exergames used in rehabilitation should avoid introducing maladaptive movements and setbacks in progression. Instead, the games should inhibit erroneous execution and implement an adaptive feedback loop to prevent that. In traditional therapy, constant feedback is either given by a therapist or through tools like mirrors. These aids support the progression of functional improvement and motivation, which is a more critical factor for patients than for therapists.

During subsequent home rehabilitation, secondary care by the patient’s family, relatives, and friends is crucial for further progression, but this depends on providing those with appropriate knowledge and tools, as stated by a therapist. Further, the therapist mentioned that therapy should challenge patients at the right level to avoid stagnation due to overexertion or under challenge.

Inefficient therapy progression can lead to mental struggle, and achieving personal goals is not only motivating but also a measure of efficacy for patients, as stated by the patients.

Qualitative and quantitative measurements should constantly monitor the efficacy of the current training and compare with known baselines and the patient’s personal goals. This helps communication between all stakeholders, adapts the training throughout the rehabilitation process, and avoids erroneous movement.

Usability

The interview participants all agreed that technology used for rehabilitation needs to be easy to use before it can be widely adopted. Current solutions need to fit more into the everyday lives of therapists and patients alongside other necessary clinical activities. This means that priorities must be made, and more essential tasks will take precedence over time-consuming and expensive activities.

Therefore, the usability of the solutions was considered crucial. One requirement for technology used in rehabilitation is that there should be little or no barrier to entry. Many therapists emphasized the need for a simple “one-button” operation to use exergame platforms. For therapists, easy onboarding and use were significant factors in reducing the threshold for adopting new technology and using it in rehabilitation.

Another essential feature of technology used in rehabilitation mentioned by the therapists is lightweight hardware. This can increase mobility and flexibility in the physical environment, making the onboarding process less daunting. The ability to move the system around makes it more useful in both clinical and home settings.

While ease of use is essential for therapists, digitization in healthcare was viewed as favorable overall. All participants were familiar with and had used exergaming platforms in their practice. The participant with the most experience emphasized the importance of a seamless setup for successful home use.

Technology

The introduction of digital tools into rehabilitation routines was received with mixed feelings. Although all parties were somewhat familiar with VR solutions and exergames, most therapists had only tried them, not incorporated them into the rehabilitation. Therefore, the patients were not offered any digital tools for their rehabilitation. Here, however, it must be mentioned that one of the therapists was linked to a rehabilitation facility that is nationally leading in the use of VR technologies in rehabilitation. The patients, on the other hand, reported being interested in incorporating such technologies into their training. The therapists, however, were more conservative in adopting new technologies in their already established routines. According to SME1, it is therefore essential to also consider the users’ technical literacy based on experience and age.

According to the therapist, the main hurdles to introducing technologies are the patients’ limited cognitive ability to use such complex systems and the therapists’ limited temporal resources to get familiar with the systems and set them up. However, their experience is based on commercial hardware, like the Nintendo Wii platform, with games not tailored to their specific needs. The therapist, however, noted that commercial games are more enjoyable, as the focus is on the game experience rather than the therapy outcome.

Technical challenges might arise for the game developers based on the specific wishes of the therapists and patients regarding the design of the exergame. Both tend towards open-air landscapes, incorporating free exploration using multiple interaction modalities, like gait, reaching, and grasping. The patients wished for tasks aligned with their goals, like walking, climbing, and fishing.

Another technological challenge could be the incorporation of adaptive real-time feedback. In response to this challenge, SME2 mentioned using machine learning models incorporated into the game to counter the adverse effects of maladaptive training. Still, for most use cases, this might be too excessive.

Motivation

Keeping patients motivated was the primary concern of the therapists. They suggested that games can help motivate patients to regain capabilities related to their hobbies and interests, even if those goals are unrealistic. Additionally, therapists highlighted the effectiveness of using milestones revolving around these activities, such as fishing or climbing, to increase motivation. Frequent goal-setting meetings were crucial for aligning short- and long-term goals.

Further, the therapists recognized that patients often become passive after transitioning to the home environment. They experienced that passivity often leads to plateauing or declining progress, decreasing motivation, and creating a negative feedback loop. To combat this, patients expressed the desire for the gaming system to promote initiation from the user, while therapists emphasized the importance of games promoting independent activity and exercise.

Patients reported that personal relationships and interactions were the strongest motivational drivers, followed by interests and hobbies. Returning to everyday life or unrestricted mobility was also important but to a lesser extent.

Social factors

Social belonging is a critical human need, so it is essential for ABI patients in their sometimes socially isolated state. A big hurdle mentioned by the therapist is that many patients experience aphasia, which makes communication a challenge. According to the therapists, this can lead to misunderstandings during goal setting, which relies on correct self-perception and communication of training exercises.

However, mutual understanding between the two parties in rehabilitation is paramount for progress and promotes motivation and setting realistic goals and safety. Besides disease-related communication, the patients expressed their trust in the therapists but less in the healthcare system. They understood their high dependency on their caregivers, especially during the early stages of recovery. Patients also mentioned that during the institutional rehabilitation, their interaction with peers helped them accept and understand their current situation and motivated them.

After release from rehabilitation institutions, the therapists reported, the patients often find themselves left alone with their rehabilitation process. Additionally, they can end up in social isolation due to loss of mobility. Most patients, however, can receive regular ambulatory therapy, which helps with the rehabilitation process and the feeling of being cared for. Besides the ambulatory teams, the social circle—including relatives and friends—plays a significant role in the progression of rehabilitation at home as secondary caregivers. However, according to the therapists, the caregivers must have the correct tools and knowledge to be sufficient in this role. If not, their support can be counterproductive and frustrating, as they tend to support the patient, thereby inhibiting his rehabilitation process.

The patients themselves see their social circle at home as a huge motivator and use specific interactions with them as personal goals for their progress. As a suggestion for incorporating social factors into an exergame, patients wished for a multiplayer function.

Ownership

The insights emphasize that ownership and inclusion are the primary motivators in the rehabilitation process of the patients. According to the subject matter expert, the patient's personal needs and goals are a crucial factor. Therapists' and patients' co-development of the rehabilitation roadmaps must start with goal setting. Realistic goal setting is essential for sustained progress, as motivation and preventing disappointment depend on it. All interview parties agreed on this point. The patient's personal goals, which often align with their previous recreational interests, social interactions with family members, or their complete independence, can be taken as the primary goal. This is then broken down into smaller, more realistic steps. However, the goals still must challenge the patient to obtain functional improvement. This might sometimes be hard for families wanting to support the patients and participate in their rehabilitation.

Further, it was mentioned that to communicate the rehabilitation progress to the patient sufficiently, therapists employ various metrics to illustrate it better. However, sufficient communication can be hindered by the patients' cognitive disabilities and must be considered during goal setting. The patients stated that poor communication can be confusing and frustrating, especially when thrown into new situations.

Patients were very positive about integrating innovative technologies into their rehabilitation process; one has done so already. Therapists are more hesitant about introducing new technologies because they have established rehabilitation methods and are afraid of the time overhead new technologies might entail.

Exemplary patient journey from incident to recovery

We used customer journey mapping to better picture a patient's journey from the occurrence of the acute brain injury via different institutions until they are back home (Rosenbaum et al., 2017). Customer journey mapping is a way of visualizing the storyline of every engagement a customer has with a service, brand, or product. We used the visualization method differently: to show the patient's journey through different institutions and her/his contact with different stakeholders and to map the patient's condition, goals, pain points, thoughts, feelings, and recovery process to each step in the rehabilitation process. We believe that this can help other stakeholders, like HCI developers, to better understand the, at times, unfamiliar characteristics of this specific user group and, thus, our final design recommendations and their application.

Stages of rehabilitation

The different stages of rehabilitation, from the occurrence of injury, till the patient is back home, are presented in Table 2. It shows the patient's condition, goals, pain points, thoughts, feelings, involved stakeholders, recovery process, and duration.

Patient scenario

Based on the patient interviews and the patient journey presented in Table 2, we developed the following scenario (Table 3) and storyboard (Figure 1). This aids the understanding of the main stakeholders' needs and pain points at various stages of their recovery.

In this study, we aimed to discover how XR-based exergames can be employed for motor rehabilitation and how this can be sustainably incorporated into the rehabilitation ecosystem. As our primary sources, we reviewed existing XR-based rehabilitation technology and used interviews with various ABI stakeholders, such as subject matter experts, therapists, and ABI patients.

Discussion

The study's key findings were eight themes related to XR-based rehabilitation that emerged from the interviews with ABI stakeholders. In the remainder of the discussion, we discuss how these can be transformed into specific design recommendations for

TABLE 2 Patient journey based on the insights gained throughout this study.

Stages of rehabilitation	Occurrence of injury	Emergency hospital	Rehabilitation hospital	Rehabilitation institution	Home
Condition of the patient What are the main symptoms?	Minimally conscious; slurred speech	Breathing problems	Muscle weakness; spasms; pain	Mental behavior and state; strength and coordination	Strength and coordination; fatigue
Patient's goals What needs to happen to move forward	Get to a hospital; Prevent further injury	Stabilize and evaluate the patient	Improve strength and coordination of essential functions	Improve physical and social abilities; become self-sufficient	Tackle everyday tasks; stay activated; balance training and rest
Pain points What are the patients struggling with?	Traumatic experience	Uncertainty; loss of independence	Dependency; acceptancy; body incapacity	Dependency; acceptancy; recovery progress not as expected	Feeling isolated; struggles emotionally
Patient thoughts What are they thinking?		Shaky short-term memory	Lack of self-awareness (understanding the severity of the situation)	Ready for more training after feeling the progress	Everyday things are hard to do; missing the help they have become used to
Patient feeling What are they feeling?		Confused; afraid; agitated	Discouraged	Hopeful; impatient	Happy but afraid; motivated at first
Stakeholders Who is involved?	Relatives	Neurosurgical team; doctors; nurses	Case coordinator: nurses, therapists, doctors	Case coordinator; therapists	Relatives: friends; community care providers
Recovery How is the progress of the recovery?	Sudden decline in health	Fast health improvement	Significant health improvement	Recovery slows down	Recovery stagnates
Duration How long does it take?	Seconds and minutes	Days	Weeks	Months	Years

TABLE 3 Summary of a plausible patient scenario using the fictive person, Michael.

Michael (41 years old)	
Accident	Michael returned to work after a long week in the mountains hiking with his family. Michael suddenly felt dizzy during work, numb in the face, and had trouble seeing. His work colleagues recognized his situation and called an ambulance, driving him to the nearest stroke unit
Clinical history	Michael was transmitted to a rehabilitation hospital after a few days in intensive care to regain lost function. Although he regained sight, he could not move most of the right side of his body. After months of training, he regained many functions and can walk 100 m (about 328.08 ft) with a walker. Otherwise, he uses a wheelchair. After confirming that Michael could do basic tasks of daily living, he was released home
Problems	He still gets tired fast, pushes too hard sometimes to improve further, and suffers burnout. He gets depressed because he cannot keep up with his children anymore. He dislikes the rehabilitation facility and training and thinks the others, mostly older patients, are boring
Improvements	He is highly motivated to get back to where he was. He has a winning mentality, no issues with understanding instructions for the training, and is competitive
Training program	He must work on upper and lower body coordination, mobility, and endurance
Goals	He wants to go hiking with his family again. He goes to work to meet his peers and have an everyday structured life. He also wants to be able to drive again to support his family better
Use of technology	Confident in using technology. He is familiar with VR, as he once used it at a theme park. However, he was never a gamer other than his children
Support network	His family consists of his wife and two children, and his parents live 1 h away. His friends, primarily work colleagues, also assist him

developing XR-based rehabilitation games. The literature concerns 2D virtual reality games, which rely on screens. In our study, however, we focus on fully immersive 3D XR-based exergames using head-mounted displays. Some of the design recommendations, however, are similar.

Another important finding of the study is the patient journey. This condensed overview was used to understand the needs of the main stakeholders, not just via a proxy. The overview shows that most of the rehabilitation takes place in the patient's home without a therapist present. At this stage in the rehabilitation process, the patient misses the help they have become used to and experiences stagnation in their recovery. Motivational rehabilitation tools are, therefore, of high importance for good progress in recovery.

Safety

Concerns about the safety of new technologies were clearly mentioned in the interviews and related literature and are essential for the acceptance of new rehabilitation tools by all

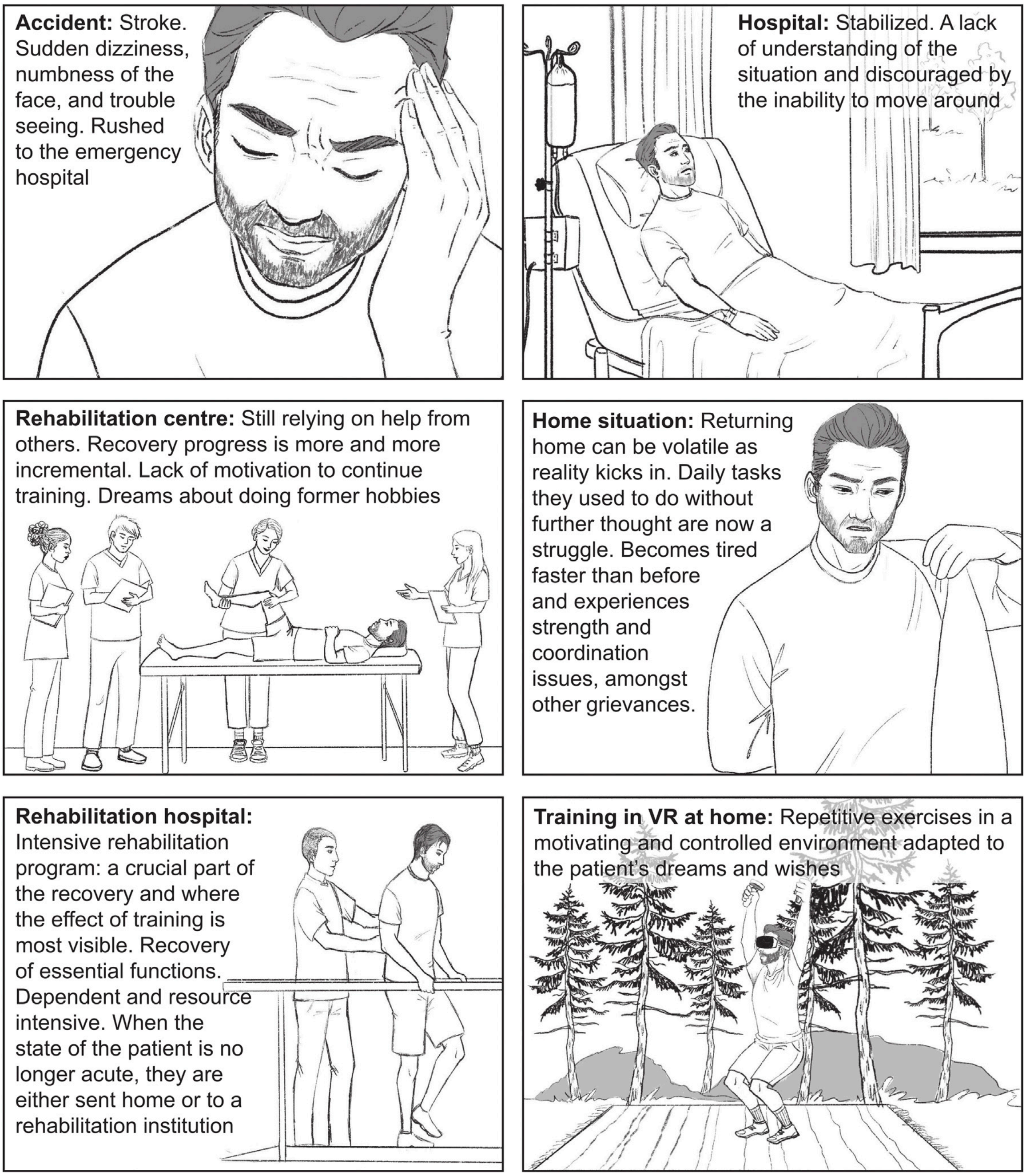

FIGURE 1
Illustration of the described patient scenario and relevant milestones during the patient's recovery. Created by Marianne Paulsen; reproduced with permission.

involved stakeholders (Jordan and King, 2011). However, only a few studies are concerned with the safety recommendations of XR provided by head-mounted displays (Jordan and King, 2011; Maggio et al., 2019). Unsafe training procedures can lead to adverse effects like pain, fatigue, dizziness, and falls (Morone et al., 2014; Rüth et al., 2023).

Our results indicated that especially the patient's disabilities and their lack of ability to judge their capabilities lead to increased risks of injury. As this is already challenging for the patients themself, understanding their limitations and identifying potential risks is even more difficult for non-matter experts, such as game developers. The individuality of the patient's disabilities and their change over time increase the difficulty for the developers even further when creating safe exergames. Therefore, the possibility of initial individualization and ongoing adaptation to the functional capabilities should be a central part of the game mechanics. Such customizations, together with good onboarding, are thought to increase accessibility via safety (Jordan and King, 2011). This can be done by finding the delicate balance between being challenging enough to promote functional improvement and easy enough to avoid injury and demotivation.

Besides the patient's current stage, the environment for which the exergames are intended is also an important safety factor. On one hand, do XR technologies allow for the training of potentially dangerous real-life situations, like participation in traffic, in the safety of one's home (Pietrzak et al., 2014). On the other hand, this could also create other risks. Home training and related exergames are often unsupervised and occur in suboptimal environments. The use of physical safety equipment, such as safety harnesses, handrails, or chairs, could be incorporated to promote safety if they do not disrupt other central design recommendations. Besides using safety equipment, Maggio et al. (2019) indicated that familiarity with the hardware and its control is a crucial element that can convey safety without the need for supervision and increase acceptability. Using such additional safety equipment, immersive VR exergames seem to be considered safe, even for home use (Broeren et al., 2008; Darekar et al., 2015; Tuena et al., 2020). So could the little-discussed application of AR add to safety during exergaming by allowing the patient to keep the relation to the physical space around him, which can avoid collision accidents or be used as additional support.

Flexibility

The rehabilitation process for individuals with ABI is highly individual due to the varying nature of the resulting functional deficits and varying personal preferences. The rehabilitation process must be adapted correctly to ensure better safety, motivation, and functional outcomes (Krishnan et al., 2023). As the XR technologies allow for the simulation of a wide variety of real-life environments, the modification of sensory presentations and feedback, and the adaption of task complexity, they can seemingly fulfill those requirements (Pietrzak et al., 2014). To make such an adaptation viable in clinical practice, creating an extensive library of exercises, easily individualizable, modular games, or applying machine learning algorithms automatically adapting to the patient's capabilities should be considered (Pirovano et al., 2013; Muñoz et al., 2019). The first two suggestions, however, need external intervention to choose the correct exercises, which can be impractical for home training. Machine learning-based approaches could assess the movement during training and adapt specific game parameters and feedback to adjust it to the patient's changing needs automatically, as suggested by SME and literature (Osgouei et al., 2020; Tharatipyakul and Pongnumkul, 2023). Although this technology has its first applications in fitness training, its feasibility in such a complex field as rehabilitation is yet to be systematically assessed.

Efficacy

For a clinical intervention, its efficacy is central for its application to be considered. As mentioned in the literature review, XR exergames showed us to be able to improve motor function and are currently considered a supplementary tool for therapy.

Clear and continuously updated therapy road maps that align with personal goals are paramount for a good progression of the rehabilitation process. Constant qualitative and quantitative measurements of the patient's performance aid both the therapist and the patient in understanding and communicating deviations from a general baseline and intervening promptly if necessary. Exergames could provide this by allowing for the personalization of individual goals and adaptable level design that considers continuous performance measurements via integrated sensor systems and reports and automatically adapts to the exercise difficulty (Osgouei et al., 2020). Giving comprehensible performance reports alongside the game can increase the patient's feeling of ownership over the rehabilitation process. By constantly pushing the current boundaries of the user's abilities to a reasonable degree, functional improvement is facilitated, but overexertion should be avoided. Especially as patients tend to overestimate their own ability, detecting eventual overtraining and promoting rest periods can prevent injuries and stagnation of the recovery (Cho et al., 2023).

Further, the game should prevent maladaptive movement, which can cause insufficient rehabilitation outcomes or even injuries. A certain degree of freedom in executing the movement is acceptable, as it provides a more enjoyable gaming experience; however, for good progress, compensatory movement should be discouraged if possible. This can be facilitated by intelligent game design or performance measurements, like movement trajectory deviations (Alankus and Kelleher, 2012).

Technology

Limitations in the technology of current systems also fail to address the needs of therapists and patients. For clinicians, introducing technology in general into rehabilitation routines is met with hesitancy. While patients are interested in incorporating novel technologies into their training, therapists are more conservative in adopting them in their established routines. The main hurdles are the limited cognitive ability of some patients to use complex systems and therapists' limited resources to get familiar with the systems and set them up. However, these experiences were based on games not tailored for rehabilitation. In contrast, like other at-home rehabilitation technologies, XR has the potential to reduce the resource requirements of motor rehabilitation programs. This can be accounted for by reducing time-consuming transportation, especially for remote patients, and facilitating labor-intensive traditional rehabilitation practices (Pietrzak et al., 2014).

Several aspects must be addressed to scale the use of XR systems in rehabilitation, especially in the home setting. The product design should focus on flexibility and ease of use rather than vast functional capabilities. Accessibility should be the priority, which also applies to the user interfaces, as the end-user might have restrictions or may not even consider trying a new technology. Therefore, changes to commercial XR hardware and setup instructions must be considered, as patients might struggle with the correct attachment of the headset, controllers, and other accessories, as done by some currently available solutions (Table 1). Meanwhile, the underlying technology offers new opportunities that could enhance the enjoyment and efficacy of the gameplay itself. Advances in hardware make personalization mechanisms feasible on smaller systems, reduce costs, and increase gameplay fidelity. Improved connectivity creates opportunities for more seamless social gameplay and remote rehabilitation interventions. No- or low-code platforms could also lower the threshold so game development can become more rapid and widespread, as Baldassarre et al. (2021) demonstrated. Lowering this threshold moves us closer to applying co-creation in the game design process and, thus, applicable applications.

Motivation

The use of exergames in rehabilitation has been extensively studied due to their inherent positive motivational aspect (Hung et al., 2016; Pacheco et al., 2020). Motivation is directly related to increased training adherence and, therefore, functional improvement (Maclean et al., 2002; Kil and Son, 2020). Due to the immersive nature of XR applications, they are seen as inherently motivational and, therefore, are investigated for their use in rehabilitation (Maggio et al., 2019).

In relation to this, our results indicate that by considering the patient's individual needs, preferences, skills, and goals, their motivation can be optimized during rehabilitation. The primary concern of therapists is keeping patients motivated throughout their rehabilitation and leveraging their hobbies and interests as key drivers. Frequent goal setting and adjustment with the patient is a critical component and serves as a reference point that can be used to monitor and display progress, which is a motivating factor. Therefore, personalized virtual environments and tasks that are constantly adjusted to the patient's current state, as well as feedback on the patient's progress and goals, should be included in the exergames.

After transitioning to the home environment, patients can often become passive and preoccupied with activities of daily living, as indicated by our interviews and the literature review. The lack of further goal setting and display of progress, a frequent activity in the inpatient phase, can lead to decreased motivation. To counteract this, patients expressed the desire for gaming platforms to promote initiation from the user, while therapists emphasized the importance of games promoting independent activity and exercise. Small nudges that keep the patient active and motivated can be deciding in maintaining progress. Incorporating the key drivers—i.e., fishing, biking, and other recreational activities—used in the inpatient phase could reinforce this.

Social factors

Social belonging and interaction are crucial for the not seldomly isolated patient group, and the importance of incorporating social play was discussed previously (Alankus et al., 2010). However, in the early stages of rehabilitation, simple communication can be challenging due to aphasia, making it difficult for patients to engage socially. As patients progress and become more independent, other complex social components become increasingly important.

Once patients transition to outpatient care, they may experience social isolation. Patients often perceive their social circle at home as a significant source of motivation and support, with family and friends acting as supplementary caregivers in many situations. In cases where ambulant supervision is infrequent or unavailable, the involvement of family and friends becomes even more vital in the rehabilitation process. Providing them with tools to assist the patient's progress can be beneficial.

Integrating social factors and mechanics into games can be an effective approach. Cooperative gameplay and competitive multiplayer are motivational mechanics in general and specifically in ABI rehabilitation (Sweetser and Wyeth, 2005). Asymmetric gameplay, shared virtual spaces, and in-game communication tools are examples of mechanics that facilitate social interaction in games. Social game mechanics need to align with general social factors to enhance motivation and increase the likelihood of user engagement and participation.

Ownership

Our research shows that the rehabilitation journey in the aftermath of an ABI involves feeling a loss of agency. This loss is perceived but also literal, as the patient often suffers significant motor and cognitive impairments. The paths of the interviewees, from the hospital to rehabilitation facilities and eventually back home, revealed a narrative of disorganized logistical practices. There was an apparent disconnect between the desires, recommendations, and actual decisions made, causing confusion and disorientation. While the experiences at the rehabilitation facilities were generally positive and productive, the lack of predictability in the process left the patients feeling a diminished sense of control and agency.

Interestingly, the most remarkable accomplishments in terms of logistics were a result of the patients' independent decision-making. This suggests they could navigate the rehabilitation journey more effectively when given the chance to make independent choices.

Ownership of the activities in the rehabilitation process enhances the sense of agency and engagement, which can significantly contribute to its efficacy (Maier et al., 2019). When patients feel a sense of ownership, they are more likely to be motivated, actively participate, and take responsibility for their recovery.

In a gaming context, fostering ownership is key to patient rehabilitation. It is crucial to give patients a sense of control over their experience and insights into their rehabilitation progress. Thus, by providing in-game customization options, such as adjusting the general game theme and, to some extent, exercises based on their interests and goals, as well as giving understandable metrics on their performance and progression, agency in decision-making can be promoted. Tailoring the game experience to their preferences can increase their engagement and motivation to participate regularly. It is important to note that transparency is paramount in implementing changes like level difficulty and performance feedback to ensure patients experience ownership and avoid confusion and frustration. When done correctly, this feedback loop can reinforce efficacy and progress (Schmid et al., 2016).

Design recommendations

We propose several design recommendations for XR-based rehabilitation games based on the emerging themes, the patient

TABLE 4 Proposed design recommendations for XR-based rehabilitation games. The source and rationale behind each design recommendation are indicated.

Theme	Design recommendation for XR-based rehabilitation games
Safety	Make it safe enough to be completely safe with supervision, ideally without[2,3]
	Adapt to each user's limitations[2,3]
Flexibility	Assess movements and automatically adjust and adapt game parameters and feedback using trained personal or machine learning[3]
	Adjustments must be quick and unproblematic, so they do not lead to errors or wasted resources 3
Efficacy	Measure and convey quantitative and/or qualitative performance data[2]
	Help the user build a better understanding of their capacity/condition[1,2]
	Show a clear connection between the exercise mode and game mode[2]
	Push the boundaries of the users' abilities[2]
	Promote rest and moderation to avoid overtraining and overconfidence[1,2]
Usability	Make it highly user-friendly with low/no barrier to entry[2]
	Make it as easy or easier to use as commercially available solutions. This should apply to primary users (patients), secondary users (therapists and caregivers), and potentially other users (social circle and relatives)[3]
	Make it easy to set up and operate, ideally "one-button"[1,2]
	Make the hardware used comfortable and non-disruptive[3]
	Make it compatible with several platforms[1]
Technology	Sensor standards and requirements must meet the fidelity that lets therapists sufficiently supervise the rehabilitation process[3]
	Make it lightweight: can be moved and relocated[2]
	Make it compatible with several platforms[1]
Motivation	The game mechanics must engage the user and incite motivation beyond standard training[3]
	Help the user regain capabilities related to hobbies and interests[1,2]
	Should promote initiation from the user[1]
	Promote independent activity/exercise[2]
	The user must like to play the game to ensure adherence[3]
Social factors	Provide the tools to handle challenges related to communication difficulties[2]
	Social interaction should be considered in the development and implementation both in and outside the game[3]
	It should have the possibility to be multiplayer[1]
Ownership	The user should feel that they have ownership of their own game experience[3]
	The user wants to be informed on rationale of certain interventions[1,2]

Data sources: 1 Patient interviews 2 Therapist interviews 3 Literature review.

journey, and the discussion above. The design recommendations are presented in Table 4, and their source and rationale are indicated for reference. These design recommendations can guide designers and developers of XR-based rehabilitation systems. While certain themes are universally applicable for all exergames in motor rehabilitation, we argue that certain themes carry greater significance when applied to XR-based rehabilitation games compared to other exergame applications. Specifically, we want to highlight five key themes: safety, usability, efficacy, technology, motivation, and ownership, which diverge in some respects from non-XR-based exergames.

Foremost among the considerations of the involved stakeholders is the safety aspect of XR-based systems, as they most notably can impede spatial orientation and increase the risk of injuries, which might be reduced by using AR environments instead of fully immersive VR environments. For all stakeholders involved, safety was of the utmost importance and was pivotal in trying any new solutions. The significance of safety is further emphasized, that besides proving clinical efficacy, new medical applications must prove their safety by complying with national and international regulations (e.g., *Directive 2007/47/EC of the European Parliament* 2007).

Although the usability of XR technologies has increased significantly over the last few years, they still require a more elaborate and unfamiliar setup than other exergame systems, such as screen-based counterparts. Thus, assistance in setup, calibration, automatic error handling, and general onboarding is essential to appeal to patients and therapists.

Moreover, the XR system offers additional sensors, including position sensors and even hand-tracking capabilities, that can be leveraged to provide realistic virtual interactions and fine-grained performance assessments, increasing clinical relevance.

The realism and customization capabilities inherent in XR technologies enable an elevated degree of personalization within environments tailored to individual users, which the end users specifically emphasized. This, in turn, cultivates heightened adherence and motivation.

Other frameworks and design guidelines have been proposed previously and highlight similar themes crucial for the successful development of exergames. While the majority of these frameworks predominantly target 2D clinical exergames, specific themes are transferable to XR at-home exergames. Further, most frameworks concentrate on adaptation and individualization strategies tailored to the diverse end-user group. This is either achieved through prior intelligent game design that incorporates the user's capabilities into account or through automatic adaptation algorithms (Hardy et al., 2015; Pirovano et al., 2016; Tadayon et al., 2020). In contrast, the framework by García-Martínez (2015) prioritizes the creation of ownership by providing appropriate feedback on performance and results. Additional recurrent themes were motivation, appropriate use of sensor technologies, the importance of social interactions, the efficacy of the digital intervention, and the sustainability of a solution (García-Martínez et al., 2015; Hardy et al., 2015; Pirovano et al., 2016; Li et al., 2020; Tadayon et al., 2020). Notably, only the framework proposed by Li et al. (2020) focuses explicitly on using head-mounted VR, guiding the design, development, and evaluation of exergames for health in a broader context.

Compared to the previously proposed guidelines, our design recommendations are an important tool for any game developer who wants to understand the central stakeholders beyond mere clinical requirements. Our recommendations extend the scope by prioritizing direct stakeholder interaction to uncover emotional needs. Moreover, by delivering the design recommendations in a brief manner with relevant contextual information, we ensure their accessibility to non-subject matter experts, including game designers or other stakeholders without a clinical background. It is important to note that while our approach facilitates the initial understanding and design phases, it does not replace the necessity for iterative co-design workshops with the central stakeholder. It enhances and accelerates the planning and execution, leading to a more comprehensive, efficient, and sustainable development journey and desirable games for the patients.

Limitations

Several limitations of this study must be acknowledged. Firstly, due to the restrictions encountered during the COVID-19 pandemic, we could only recruit a limited number of interviewees, all of whom were reached exclusively online. While this approach ensured adherence to health guidelines and timely completion of the interviews, it inevitably narrowed the diversity of perspectives included in our research. Furthermore, it is essential to note that specific stakeholders, like family and friends of patients, game developers, and municipalities, who could have contributed different perspectives, were not included in our study. The absence of these perspectives may result in an incomplete picture of the subject matter.

Secondly, our research is geographically limited to Norway. Although this localized focus seems disadvantageous as it limits the generalizability of our findings to a global audience, this can also be seen as the opposite. The potential to highlight the impact of remoteness of the end-user can aid in understanding the challenges of in-home rehabilitation.

Lastly, it is essential to emphasize that further validation and verification of these findings is advised to ensure the robustness and reliability of our research outcomes and aid in a potential framework for designing in-home XR-based rehabilitation games.

Conclusion

Based on contemporary research, existing commercial solutions, and interviews with subject matter experts, healthcare professionals, and patients, we found several important considerations for home-based rehabilitation exergames for lower-limb motor rehabilitation. Guided by the principles of human-centered design (HCD), our objective was to uncover the needs and prerequisites of individuals undergoing motor rehabilitation and turn these into design recommendations for game developers.

In summary, our recommendations address both system-oriented demands, encompassing sensor fidelity, usability, flexibility, and efficacy, and human-centered considerations, including user engagement and motivation, satisfaction, social interaction, patient participation, and ergonomics. Although existing technologies meet the requirements for their use in motor rehabilitation, market players struggle to seamlessly integrate their solutions with the patient's needs at various stages. Notably, challenges emerge regarding flexibility, usability, patient participation, and social factor integration. Further, XR-based exergames especially lag behind their traditional non-immersive counterparts. These solutions exhibit less certainty in quality, usability, and efficacy, raising concerns about potential adverse effects on motor rehabilitation.

Future research must consider additional stakeholders, notably those responsible for infrastructural facets, such as management and developers. In addition to our current findings, such collaboration is essential to create and evaluate a robust, developer-friendly framework facilitating the development of utilitarian home-based rehabilitation games for lower-limb neurorehabilitation.

Data availability statement

The datasets presented in this article are not readily available because the local data protection office does not allow for the publication of interview recordings. Requests to access the datasets should be directed to emanuel.a.lorenz@ntnu.no.

Ethics statement

The studies involving humans were approved by the Sikt—Norwegian Agency for Shared Services in Education and

Research (Reference number: 250396). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

EL: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing–original draft, Writing–review and editing. AB: Data curation, Formal Analysis, Investigation, Methodology, Writing–original draft, Writing–review and editing, Conceptualization. ML: Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing–original draft. OA: Supervision, Visualization, Writing–review and editing, Conceptualization, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Robotic systems for upper-limb rehabilitation in multiple sclerosis: a SWOT analysis and the synergies with virtual and augmented environments

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The robotics discipline is exploring precise and versatile solutions for upper-limb rehabilitation in Multiple Sclerosis (MS). People with MS can greatly benefit from robotic systems to help combat the complexities of this disease, which can impair the ability to perform activities of daily living (ADLs). In order to present the potential and the limitations of smart mechatronic devices in the mentioned clinical domain, this review is structured to propose a concise SWOT (Strengths, Weaknesses, Opportunities, and Threats) Analysis of robotic rehabilitation in MS. Through the SWOT Analysis, a method mostly adopted in business management, this paper addresses both internal and external factors that can promote or hinder the adoption of upper-limb rehabilitation robots in MS. Subsequently, it discusses how the synergy with another category of interaction technologies - the systems underlying virtual and augmented environments - may empower Strengths, overcome Weaknesses, expand Opportunities, and handle Threats in rehabilitation robotics for MS. The impactful adaptability of these digital settings (extensively used in rehabilitation for MS, even to approach ADL-like tasks in safe simulated contexts) is the main reason for presenting this approach to face the critical issues of the aforementioned SWOT Analysis. This methodological proposal aims at paving the way for devising further synergistic strategies based on the integration of medical robotic devices with other promising technologies to help upper-limb functional recovery in MS.

KEYWORDS

multiple sclerosis, robotics, rehabilitation, SWOT, virtual reality, augmented reality, digital health

1 Introduction

The extraordinary growth of robotic applications to rehabilitation has offered multiple solutions for the most demanding issues of people with disabilities (Carbone and Gonçalves, 2022; Pierella and Micera, 2022; Sadeghnejad et al., 2023). Among these challenges, we can find the impairments caused by Multiple Sclerosis (MS), a complex disorder of the central nervous system, showing a spectrum of sensory, motor, autonomic, and cognitive difficulties that severely affect a person's capability to perform several Activities of Daily Living (ADLs) (Dobson and Giovannoni, 2019; Lublin et al., 2022). The signs and symptoms of MS are the consequence of underlying neuropathologic changes that occur in the central nervous system (CNS). The primary mechanism of injury is inflammatory demyelination and, to a variable degree, axonal damage (Lublin, 2005). The classification of MS into subtypes plays a crucial role in both prognosis and treatment decisions. The four subtypes of MS, namely, Relapsing-Remitting MS (RRMS), Primary Progressive MS (PPMS), Secondary Progressive MS (SPMS), and Progressive-Relapsing MS (PRMS), are characterized by distinct clinical manifestations (Lublin et al., 2014; Giovannoni et al., 2016). During RRMS, inflammatory attacks on myelin and nerve fibers cause visual impairments, tingling and numbness, fatigue, intestinal and urinary system disorders, spasticity, and learning and memory impairment. PPMS mainly affects the nerves of the spinal cord, leading to walking difficulties, weakness, stiffness, and balance problems. SPMS is considered the second phase of RRMS and affects around 65% of patients, causing increased weakness, fatigue, stiffness, mental disorders, and psychological impairment. PRMS is the rarest type of MS and affects approximately 5% of patients, presenting symptoms like eye pain, double vision, sexual, intestinal, and urinary system dysfunction, dizziness, and depression (Ghasemi et al., 2017).

Roboticists explore the potential of smart mechatronic devices in the domain of MS by approaching the inter-individual variability and unpredictable progression of the disease to provide patients with dynamic and personalized approaches to rehabilitation (Lamers et al., 2018; Duan et al., 2023; Podda et al., 2023). By offering precise and versatile tools to clinicians, the field of biomedical robotics contributes to both studying and treating this multifaceted disease (Rajavenkatanarayanan et al., 2019), especially in terms of motor impairments due to symptoms like muscle weakness, spasticity, fatigue, tremors, coordination difficulties, and deficits in postural and motion control. We should also ponder how motor-cognitive impairments are a priority that is also targeted by the developers of robots for rehabilitation in MS. However, barriers to the introduction of these solutions in clinical settings exist, especially considering the specific symptoms of the disease (e.g., spasticity could exclude the use of devices mechanically acting on the individual's limbs for assisting the recovery of other skills, like cognitive ones) and the cost of purchasing the devices. Nevertheless, opportunities in this domain definitely exist alongside the potential for responses to the aforementioned challenges. The recent reviews by Straudi et al. (2022) and Dixit and Tedla (2019) have highlighted the need for additional high-quality trials with sufficient sample sizes and methodological rigor to draw definitive conclusions about the effectiveness of the clinical application of robotic-assisted upper limb-therapy in MS. This manuscript explores upper-limb robotic rehabilitation in MS through a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) (Rizzo and Kim, 2005; Nwosu et al., 2019). The objective of this review is to exploit this approach to elucidate the potential of robotics in MS rehabilitation by providing a comprehensive perspective and addressing future research in meeting the evolving needs of the field. While conventionally employed to assess factors influencing a company's competitive position, SWOT analysis transcends the business realm and can be employed in diverse fields. Rizzo and Kim (2005) has served as a precedent of prior use of SWOT analysis in Virtual Rehabilitation and Therapy, highlighting the versatility of this framework beyond traditional business applications. Essentially, this framework assists in planning and organizing any human endeavors, helping find the internal strengths and weaknesses and the external trends (opportunities and threats) faced by the entity. This approach aimed to stimulate the proposal of innovative solutions able to exploit identified strengths, address acknowledged weaknesses, capitalize on available opportunities, and mitigate potential threats. Applied to our context, the SWOT analysis wanted to be a methodological contribution aimed at proposing a business-oriented perspective that can support a patient-centered approach, taking into consideration market access issues as well. Additionally, this discussion is integrated with a debate on how the synergy between robotic devices and interactive systems, particularly virtual and augmented settings, might be a solution to enhance the hidden potential of robotic rehabilitation alone for People with MS (PwMS). The potential of virtual/augmented systems in engaging PwMS, and also providing clinicians with adaptable options for improving treatments, is quite well-known in the literature (Calabrò et al., 2017; Russo et al., 2018). The choice of analyzing if these solutions can move upper-limb rehabilitation robotics in MS beyond its state-of-the-art is an example we present to the community of researchers, developers, clinicians, patients, and all stakeholders. We expect that other solutions can be explored, obviously, according to the framework we propose here. On the other hand, this choice will be fully elucidated after the first two sections. We will commence by exploring the features of robot-based upper-limb rehabilitation in MS, followed by a comprehensive SWOT analysis of these solutions. Subsequently, we will delve into the world of virtual/augmented systems for rehabilitation in PwMS and examine the synergies between these latter and robotic devices, discussing their transformative potential and impact.

2 Robot-based upper-limb rehabilitation for PwMS

Robotic devices have been increasingly used in neurological rehabilitation due to their ability to provide repetitive and highly reproducible motor movements, leading to positive results in motor learning and in the development or restoration of motor pathways (Krebs et al., 2007; Vergaro et al., 2010; Lo and Xie, 2012). Besides allowing for intensive training, these technologies offer the opportunity to measure real-time performance and assess the sensorimotor function of one's limb (Iandolo et al., 2019). In the context of MS rehabilitation, several studies have investigated the use of different

TABLE 1 Publications organized according to the robotic devices used.

Robotic device	Publications
Braccio di Ferro	Vergaro et al. (2010); Carpinella et al. (2009, 2012); Solaro et al. (2020); Basteris et al. (2011); Groppo et al. (2017)
Wristbot	Mannella et al. (2021)
Armeo Spring	Gijbels et al. (2011); Sampson et al. (2016); Manuli et al. (2020b)
Haptic Master	Feys et al. (2015); Maris et al. (2018); Octavia and Coninx (2014); Tedesco Triccas et al. (2022)
Phantom	Feys et al. (2009); Xydas and Louca (2012)
Amadeo	Gandolfi et al. (2018)

upper-limb robotic devices, including both research prototypes and commercial devices.

The search for relevant studies was conducted in PUBMED, SCOPUS, IEEE, Cochrane Library, Physiotherapy Evidence Database (PEDro), on papers published up to May 2023. To ensure the inclusion of pertinent literature, we established specific criteria to guide our selection process: in the title, abstract and keywords, we looked for rehabilitat ∗ AND multiple sclerosis AND robot ∗ /exoskeleton/end-effector/haptic device AND upper/hand/arm/wrist/fingers. In this manuscript, we considered the terms "robot" and "haptic interface" as interchangeable to refer to a robotic device that is used to guide, perturb, or restrict the movements of a person in direct contact with the robot's end effector (Harwin et al., 2006). We excluded any review and all those publications in which either robotic devices were used only for the assessment of upper-limb function in MS or no person with MS have been tested. This approach allowed us to identify 19 publications that met our criteria. Among these, two papers (Tramontano et al., 2020a; Tramontano et al., 2020b) were excluded. Indeed, although the authors defined the training protocol as "robot-based rehabilitation" (Tramontano et al., 2020b), the system involved there was Pablo, which is a sensor-based technology that lacks any controlled haptic feedback. Therefore, we deemed it inappropriate for inclusion in our manuscript. The resulting list of papers can be found in Table 1, organized according to the device employed in the study. The devices, which are listed and briefly described in Section 2.1, include two research prototypes (Braccio di Ferro and Wristbot) and four commercialized robots. All of them can employ haptic feedback to simulate a diverse and adaptable environment, incorporating visual, auditory, kinesthetic, and proprioceptive stimulations.

Overall, PwMS have provided positive feedback about the use of robotic devices and reported high scores regarding the perception of motor and mental wellbeing after undergoing customized training (Manuli et al., 2020b). Indeed, motivation is a crucial predictor of treatment success (Grahn et al., 2000), and the use of robotic devices in rehabilitation has been shown to be an attractive tool that allows users to embrace a positive attitude without feeling stressed or pressured.

After briefly describing the robotic systems used for upper limb rehabilitation in PwMS (Section 2.1), a SWOT analysis will be employed to investigate the use of robotic devices for upper-limb rehabilitation in PwMS. The following sections will describe and discuss the emergence of Strengths and Weaknesses of robotic technologies for rehabilitation as evidenced by research in the field. The second half of the SWOT analysis will provide readers with possible future Opportunities and Threats that are emerging from external factors and developments in related fields. Figure 1 summarizes the SWOT analysis presented in Sections 2.2–2.5.

2.1 Robotic systems used for upper limb rehabilitation in PwMS

1. Braccio di Ferro (Casadio et al., 2006) is a haptic planar manipulandum with 2 Degrees of Freedom (DoFs). The robotic device has a rigid structure and two brushless motors that offer full back-drivability, and low intrinsic mechanical impedance. The rotations of the shoulder and elbow determine and are determined by the kinematics of the hand, which grasps the device through a handle.
2. Wristbot (Iandolo et al., 2019) is a manipulandum that allows 3-DoF wrist rotations in a human-like range of motion. Grasping the handle of the device, the Wristbot assures low inertia and gravity compensation during the user's active motion, but it is also able to provide the torques needed to manipulate the wrist joint during passive or assistive modalities.
3. The Armeo Spring (Hocoma AG, Volketswil, CH) (Gijbels et al., 2011) is a 5-DoF (3 in the shoulder, 1 in the elbow, 1 in the forearm) orthosis without robotic actuators. The adjustable mechanical arm allows variable levels of gravity support by a spring mechanism, that enables users with residual upper limb function to achieve a larger active range of motion (ROM) within a 3-dimensional workspace.
4. The Haptic Master (MOOG, Nieuw-Vennep, NL) (Feys et al., 2015) is a commercially available end-effector-based robot that allows 3-dimensional movements with 6-DoFs. Three actuated DoFs are for positioning and three non-actuated DoFs are for orientation in the gimbal. This configuration permits the person to freely orient, open and close their hand as needed to manipulate an object.
5. The Phantom (SensAble Technologies Inc., MA, United States) (Feys et al., 2009) is an end-effector haptic device, controlled by 3 motors. It is handled through a pen-like stylus which provides force feedback in 3-DoFs. Unrestricted movements of the shoulder, elbow, and wrist joints are possibly involved during its use.
6. Amadeo (Tyromotion GmbH) (Gandolfi et al., 2018) is a 5-DoF device for hand rehabilitation. Amadeo can provide position-based passive, active, and assistive training modes, centered on the flexion and extension of each finger. The moving finger slides are attached to the fingers using a small magnetic disc and adhesive tape for connection to the robot. The slides then transfer, bending or stretching, movements to the fingers.

Internal Factors	External Factors
Strengths	*Opportunities*
Possibility to build dynamic environments	General technological advancements
Personalized assistance during motor training	Promotion of digital health technologies
Task-specific treatment with haptic feedback	The rapid surge of interest in home rehabilitation due to COVID-19
Synchronization with different devices	
Weaknesses	*Threats*
Challenges posed by MS symptoms	Safety issues when dealing with spasticity
Limitations due to varied disease severity responses	Risks related to unsupervised therapy
Device constraints and accessibility	

FIGURE 1
Summary of SWOT analysis for robotic rehabilitation in PwMS.

2.2 Strengths

2.2.1 Possibility to build dynamic environments

A prerequisite for both robot- and therapist-assisted rehabilitation is that individuals must maintain their ability to adapt to new dynamic environments (Shadmehr and Mussa-Ivaldi, 1994). Indeed, implicit motor adaptation may be able to reshape the altered sensorimotor mappings and contribute to cortical reorganization, potentially limiting the consequences of irreversible tissue damage in normal-appearing brain tissue and MS lesions (Reinkensmeyer et al., 2004; Rocca et al., 2005). For this reason, adaptive training protocols that introduce unfamiliar dynamic environments for individuals to adapt to, rather than simply assisting them during movement practice, may be beneficial to PwMS (Patton and Mussa-Ivaldi, 2004). Although PwMS have demonstrated residual capabilities for sensorimotor adaptation in arm and posture control, cerebellar deficits have been linked to difficulties in adapting to novel dynamic environments (Maschke et al., 2004; Smith and Shadmehr, 2005). It has been shown that individuals with cerebellar degeneration lose the motor learning mechanism based on the feed-forward control component and involved in motor adaptation (Maschke et al., 2004; Smith and Shadmehr, 2005). Individuals with MS still display this mechanism, albeit impaired (Leocani et al., 2007; Casadio et al., 2008) in such a way that could contribute to the coordination deficit and tremor associated with MS. Since force field adaptation exercises can train this feed-forward control mechanism, they may be effective in reducing tremor, improving upper limb coordination, and reducing disability in PwMS. Adaptive training may, therefore, be a promising rehabilitation approach for PwMS who exhibit various types and degrees of deficits. In the literature, this approach based on targeting sensorimotor adaptation in dynamic environments can be found in some protocols tested on PwMS (Carpinella et al., 2009; Vergaro et al., 2010; Basteris et al., 2011; Solaro et al., 2020). All these cited studies employed the Braccio di Ferro (Casadio et al., 2006) to develop an 8-session-long rehabilitative protocol involving robot-based reaching movements. In some of these studies (Carpinella et al., 2009; Basteris et al., 2011; Solaro et al., 2020), the task consisted of a series of reaching movements with a position-dependent resistive force directed along the line that connected the end-effector to the target, designed to challenge muscle weakness. However, the instability of the environment was given by additional force fields: a velocity-dependent force perpendicular to the instantaneous movement direction in Carpinella et al. (2009), and a virtual point mass connected to the subjects' hand through a linear spring, that acted as "virtual tool", in the remaining studies (Basteris et al., 2011; Solaro et al., 2020). Differently, in the protocol of Vergaro et al. (2010), by means of an iterative procedure, the robot learned the forces necessary to generate a perturbation directed orthogonally with respect to the trajectory that, for each target direction, either enhanced or decreased the lateral deviation of the average trajectories of the subject, estimated during a baseline session. Indeed, the procedure used in some works (Vergaro et al., 2010; Basteris et al., 2011; Solaro et al., 2020) was to calculate forces and spring stiffness at the beginning of each session and to let the protocol adapt its difficulty to the subject's specific impairment and the improvements - if any - that occurred from session to session. The results of these works showed that PwMS revealed a preserved ability to adapt to robot-generated forces, greater in subjects with non-cerebellar symptoms (Solaro et al., 2020). In particular, subjects showed smoother and more linear movements (Vergaro et al., 2010; Solaro et al., 2020) over and within sessions. In addition, several studies have reported a significant improvement in the Nine-Hole Peg Test (9HPT) following training (Carpinella et al., 2009; Vergaro et al., 2010; Basteris et al., 2011; Solaro et al., 2020), indicating a potential transfer of therapy benefits to activities of daily living. Although the 9HPT primarily assesses manual dexterity, it requires coordination of the entire limb. Therefore, even though when using Braccio di Ferro the hand is not actively involved in the reaching exercise, the improvement observed in the 9HPT may be linked to enhanced coordination in the elbow and shoulder.

2.2.2 Personalized assistance during motor training

Robotic devices are capable of providing haptic feedback in a controlled manner, not only to perturb the environment but also to assist in movement execution. Given the wide variety of symptoms and their different severity in PwMS (Lublin et al., 2014), assistance should be tailored according to the motor skills of the individual (Casadio and Sanguineti, 2012; Gassert and Dietz, 2018). Assistance can take the form of gravity support, guidance through specific movement patterns, or help with movement completion. A concern when providing excessive assistance is the "Slacking" effect (Casadio and Sanguineti, 2012), which refers to a reduction in voluntary movement control caused by repetitive passive mobilization of the limbs. To avoid this, a potential solution is to implement the real-time tailoring of the assistance according to the individual's needs and actual abilities. This "assistance-as-needed" approach seeks to reduce the risk of patients becoming overly reliant on robotic assistance, which could decrease their level of participation and hinder the potential for neuroplastic changes (Wolbrecht et al., 2008). Robot-based personalized assistance has been used with PwMS in several studies (Xydas and Louca, 2012; Groppo et al., 2017; Mannella et al., 2021) employing the Braccio di Ferro (Casadio et al., 2006), the Wristbot (Iandolo et al., 2019) and on an end-effector haptic device handled through a pen-like stylus comparable to the PHANTOM (Xydas and Louca, 2012). The study of Groppo et al. (2017) proposed a 23-session-long protocol to deal with the progressive worsening of motor functions in one PwMS. This multidisciplinary protocol involved traditional occupational therapy and a robot-based task, during which the subject performed center-out reaching movements. After 2 s from the movement onset, unless the subject was able to reach the target on their own, a minimally assistive force modulated according to the hand speed was generated by the robot. Groppo et al. (2017) found signs of improved motor control, given the significant increase in both the velocity and the smoothness of arm trajectories during robot-based reaching movements. Additionally, the fMRI revealed that multidisciplinary rehabilitation in MS seems to be clinically efficacious and to have a significant impact on brain functional reorganization in the short-term (Groppo et al., 2017). Mannella et al. (2021) trained the most affected limb of 7 PwMS in a 4-week robot-based program. The task was a continuous tracking of a figure targeting continuous movements in the flexion/extension and radial/ulnar deviation 2-dimensional space, in the presence of an assistive force. The force was implemented as a spring pulling the subject toward the target, and its rigidity was modulated within and between sessions, according to the performance of the subject in terms of accuracy in tracing the path. Actually, when the performance reached a specific level, assistance switched to resistance and pushed the subject far from the target, thus generating a dynamic environment to which to adapt. Similarly to what was found by Groppo et al. (2017), at the end of the treatment period, the authors detected a greater motor accuracy and control (Mannella et al., 2021), quantified by lower errors in tracking and tracing the target. In contrast, Xydas and Louca (Xydas and Louca, 2012) proposed an augmented version of the 9HPT, which incorporates assistive forces to transform it into a physiotherapy and rehabilitation system. The system included adaptive assistive forces based on healthy users' reference target trajectories and was evaluated in a single session by three PwMS. The results showed a potential improvement in the upper limb performance in 3-dimensional reaching tasks, indicating that the system could be effectively used for rehabilitation in complex movements. Analogously to the personalization of the level of assistance, Octavia and Coninx (2014) adapted the difficulty level of the training tasks proposed. Based on the information about the training progress of the subject, the algorithm determined if and how the difficulty level should have been adapted. The study revealed that the participants followed different training patterns and progression, thus confirming the need for personalized levels of difficulty. This adaptive personalized training has shown to be beneficial and appreciated by users (Octavia and Coninx, 2014).

2.2.3 Task-specific treatment with haptic feedback

Robotics allows for repetitive and consistent motor movements at high dosages, however, repetition alone, without usefulness or meaning in terms of function, is not enough to produce increased motor cortical representations (Bayona et al., 2005). Rather than on the specific impairment, rehabilitation should focus on task-specific training to improve the performance in functional tasks through goal-directed practice and repetition. Task-specific training means practicing context-specific motor tasks while receiving some form of feedback (Schmidt and Lee, 1988). Robot-aided haptic feedback is a promising approach for rehabilitation, as it can provide information to supplement or substitute visual and auditory cues (Demain et al., 2013). This kind of feedback can help internalize the movements and increase proprioceptive awareness, thereby enhancing motor learning (Winter et al., 2022). Motor learning and skill acquisition are able to elicit the functional reorganization of cortical areas and the development of new motor pathways to restore limb function (Plautz et al., 2000). The Haptic Master has been used by a few studies (Octavia and Coninx, 2014; Feys et al., 2015; Maris et al., 2018) to train PwMS in an 8-session-long robot-based protocol additional to the conventional therapy. All exercises required accurate and stabilized end-positions to successfully perform the task-oriented movements. The exercises varied in the number of movement directions (1-2-3D), the haptic environment, the precision level and type of required movements, and the cognitive load. At the end of the training, movement tasks in three dimensions, measured with the robot, were performed in less time and more efficiently (Feys et al., 2015). Significant improvements were found in Maris et al. (2018) for shoulder ROM, handgrip strength, perceived strength, and Wolf Motor Function Test (WFMT) activities. Tedesco Triccas et al. (2022) investigated the impact of the intervention of Maris et al. (2018) on patients' lives: 1) Participants felt that there was a positive impact of the training on strength, endurance, and during activities of daily living; 2) Participants expressed feelings of motivation and self-improvement about the system usage. Similarly, Gijbels et al. (2011) employed the Armeo Spring system to develop a mechanical-assisted therapy involving repetitive and active exertion of goal-directed movements, during the practice of complex motor tasks. The 8-week-long protocol, additional to conventional therapy, included the repetition of 5 tasks, ranging from gross movement, over more precise movement, to subtle strength-dosed movement. Significant gains were found in functional capacity tests [Upper extremity performance test for the elderly (TEMPA), 9HPT, Action Research Arm Test (ARAT)], particularly in subjects whose upper limb function was mostly affected at baseline. Gandolfi et al. (2018) compared two approaches for a 5-week-long training: a robot-assisted hand training using Amadeo that was mainly focused on visual feedback and had a task-specific approach, and a robot-unassisted training that dealt with functional movement and context-specific training. Both training protocols shared common features such as unilateral training, mobility, stretching, and exercise progression. However, only the robotic training involved more intensive, repetitive, and task-specific exercises. The main finding of this study was that upper limb activity and function improved after both treatments but only the robot-assisted hand training reported significant improvements in the assessment of skills in the life habits domain (Motor Activity Log (Taub et al., 1993)). In addition, preliminary observation of muscular activity showed enhancement of the extensor carpi radialis activation only in the robot-assisted group, suggesting a task-specific effect of this training mode on muscle activity. Finally, Feys et al. (2015) tried to investigate which types of robotic outcome measures could be clinically relevant. The protocol lasted 4 weeks and involved tasks that required motor accuracy, ROM, and the ability to exert high-speed movements, with different levels of assistance and difficulty. Significant correlations were found between specific functional measures (specifically ARAT and Purdue pegboard test) and movement tasks.

2.2.4 Synchronization with different devices

Robotic devices offer the opportunity to be synchronized with other electronic systems, in order to assess a broader set of body signals (Rizzoglio et al., 2020), deliver external additive feedback (Cuppone et al., 2016) and apply therapeutic stimulations (Sampson et al., 2016). The core instances of systems synchronized to robots are screen displays on which visual feedback of the virtual reality environment associated with the task is provided. Apart from these, it is hard to find examples of the use of devices in combination with robots for the rehabilitation of PwMS. The only study that apply was conducted by Sampson et al. (2016), combining the Armeo Spring (Sanchez et al., 2004) with Functional Electrical Stimulation (FES). The protocol was tested on 5 PwMS and involved 18 sessions. The robot provided kinematic data to a real-time processor that interfaced with custom FES hardware and the display. FES has been shown to be effective in augmenting strength in stroke (Glinsky et al., 2007) and spinal cord injury (Martin et al., 2012) and in reducing motor fatigue in MS (Chang et al., 2011). Through advanced model-based controllers, the passive robotic arm support combined with FES was meant to improve movement quality by promoting accuracy and voluntary effort and to increase the intensity of the intervention with minimal therapist input. Promisingly, the results showed improved accuracy of tracking performance both when assisted and unassisted by FES, a reduction in the amount of FES needed to assist tracking, and a decreased impairment in the arm trained.

2.3 Weaknesses

2.3.1 Challenges posed by MS symptoms

In Section 1, we have presented the classification of MS in the various subtypes and their associated symptoms. Among the five most common symptoms there are weakness/numbness in one or more limbs and visual impairments, such as painful monocular visual loss or double vision (Rolak, 2003). Both these symptoms result in a crucial weakness of robotic rehabilitation in PwMS. The robotic devices employed for PwMS rehabilitation are designed for unilateral use: when both limbs are affected and need to be trained, they have to undergo the training subsequently and not simultaneously. This procedure needs a longer duration of each rehabilitative session and requires moving the device and repositioning the user. A possible, but expensive and not always feasible, solution would be to synchronize two robotic devices to allow bimanual tasks and reduce downtime (Albanese et al., 2023). On the other side, visual impairments play a crucial role since all the studies about rehabilitation in PwMS (Carpinella et al., 2009; Feys et al., 2009; 2015; Vergaro et al., 2010; Basteris et al., 2011; Gijbels et al., 2011; Xydas and Louca, 2012; Octavia and Coninx, 2014; Sampson et al., 2016; Groppo et al., 2017; Maris et al., 2018; Solaro et al., 2020; Mannella et al., 2021; Tedesco Triccas et al., 2022) employed visual feedback as the main informative feedback to users. Indeed, these studies involved a virtual environment displayed on a screen and all of them required the absence of visual deficit as an eligibility criterion to participate in the study. The issue here is that visual impairments could affect subjects' performance, impacting both their motor skills and their motivation. Despite being a weakness, robots allow adding other feedback, such as auditive or haptic, to replace or be integrated with the visual one to allow conducting the training. Finally, we need to take into account that 40%–70% of PwMS reveal cognitive symptoms, such as memory loss and dementia (DeLuca et al., 2015). As for visual impairments, most rehabilitative protocols are not meant to deal with cognitive deficits and require a minimum score in cognitive assessment tests as inclusion criteria. Among these tests, a Montreal Cognitive Assessment (MoCA) (Ng et al., 2015) score >15 was required by Manuli et al. (2020b) and a Mini-Mental (Pfeiffer, 1975) >24 by other studies (Carpinella et al., 2009; Gijbels et al., 2011; Gandolfi et al., 2018; Solaro et al., 2020).

2.3.2 Limitations due to varied disease severity responses

Despite the potential benefits of robotic devices in the rehabilitation of neurological conditions (neurorehabilitation), their application is limited by difficulties in the integration between patient and machine, as well as by the variability of clinical conditions among patients, which may contribute to these difficulties. Guidelines offered by both Resquín et al. (2016) and Huang et al. (2017) emphasize the importance of careful patient selection criteria for robotic rehabilitation. For instance, among stroke patients, they suggest admitting only patients with moderate motor skills based on the Fugl-Meyer and Motor Assessment Scale scores. Previous studies indicate that robotic training is more beneficial for individuals with moderate to severe deficits, while those with better motor function do not experience greater benefits from innovative device training compared to conventional training (Duncan et al., 1983; Kim et al., 2010; Morone et al., 2011). Given this and the high variability in MS severity, the inclusion criteria employed by the studies of robotic rehabilitation for PwMS have requirements concerning minimal motor skills and minimal levels of disability. These criteria involved the Motricity Index (Collin and Wade, 1990) between 50 and 84 (Gijbels et al., 2011) or between 14 and 25 considering only the performance of the shoulder (Maris et al., 2018), the Expanded Disability Status Scale (EDSS) (Kurtzke, 1983) < 7.5 (Carpinella et al., 2009; Manuli et al., 2020b; Solaro et al., 2020) or between 1.5 and 8 (Gandolfi et al., 2018), the 9HPT (Kellor et al., 1971) score between 30 and 180

(Carpinella et al., 2009; Solaro et al., 2020) or 300 (Gandolfi et al., 2018) seconds.

2.3.3 Device constraints and accessibility

There are several general considerations that need to be taken into account about the mechanical design of the devices used for robotic rehabilitation in PwMS. For instance, to simulate realistic daily actions, the devices must provide an adequate number of DoFs to allow for proper joint rotations. However, it is natural that some of the devices used in rehabilitation have limitations in this regard. For example, the Braccio di Ferro allows for elbow flexion/extension and shoulder internal/external rotations but only permits planar movement (Casadio et al., 2006). The Amadeo focuses on finger flexion/extension without allowing abduction and adduction (Gandolfi et al., 2018), while the Armeo Spring enables only forearm pronation and supination and is not intended to enable other wrist movements (Gijbels et al., 2011). Furthermore, although most of the devices presented in this context target the upper limb, they are designed to mobilize and measure only some of the upper limb joints. The Amadeo and Wristbot devices measure finger movements and wrist rotations, respectively, while other joints are not assessed and are held in place (Iandolo et al., 2019). The Braccio di Ferro and the Armeo Spring measure and control the shoulder and elbow joints, but the movement of the wrist (except for forearm pronation/supination in the Armeo Spring) is constrained. In contrast, the Haptic Master and the PHANTOM allow all the upper-limb joints to move freely, and the position of the end-effector determines their configuration and *vice versa* Feys et al. (2009, 2015), in the same way as it happens during usual interactions with objects. In addition to these constraints, both the affordability and accessibility of robotic devices should be considered in this analysis. While robotic-based rehabilitation has been shown to be effective, the cost and limited availability of these devices remain an issue. Despite being commercially available, robotic devices are not mass-produced, and their cost remains high (Laut et al., 2016). Considering PwMS frequent difficulties in walking and moving independently, it would be an added value to make robot-based rehabilitation more accessible, by setting such systems in undersupervised environments outside of treatment centers.

2.4 Opportunities

2.4.1 General technological advancements

Robot-based MS rehabilitation will be definitely interested in the technological advancements that are currently involving the field of robotics. Rapid advances in digital electronics, hardware speed and accuracy, and fabrication techniques (Bezzo et al., 2015; Gopura et al., 2016) have played a crucial role in lowering the expenses associated with the production of both research prototypes and commercial products. The emergence of real-time control software, combined with the significant reduction in computing costs, has led to the development of a plethora of sophisticated and accurately controlled robotic devices for rehabilitation (Nizamis et al., 2021). Furthermore, advances in software, signal processing, and machine learning are expected to continue offering incremental contributions to technologies and algorithms for neurorehabilitation at an ever-increasing pace (Nizamis et al., 2021). The use of large amounts of data to implement machine-learning approaches could be facilitated by improving the overall networking between devices. Overall, the ongoing multidisciplinary approach is currently encouraging further synergies between traditional research in physics and engineering, chemical, biological, and medical science to develop new applications and acquire new capabilities.

2.4.2 Promotion of digital health technologies

The goal of digital health is to improve healthcare outcomes, increase efficiency, and reduce healthcare costs by leveraging technology to optimize healthcare delivery and patient care. It encompasses a wide range of applications, including telemedicine, electronic health records, health data analytics, genomics, artificial intelligence, and mobile health apps. These technologies are being applied in various aspects of medicine, such as diagnosis, treatment, clinical decision support, care management, and care delivery (Mathews et al., 2019). Since the great promise held for improving healthcare outcomes, increasing efficiency, and reducing healthcare costs, the digital health sector has seen significant investment (Health, 2018). Digital health technologies provide a wealth of valuable data and connectivity, significantly amplifying the potential of robotics within healthcare. These technologies excel in the collection and storage of extensive patient data. By utilizing these vast datasets, it becomes feasible to identify critical trends and patterns, thereby strengthening research and the development of treatment strategies (Chang, 2023). Robotic systems can leverage this data to deliver personalized care, make real-time treatment adjustments, and facilitate monitoring, both in on-site and remote scenarios (Zhu et al., 2007; Barzilay and Wolf, 2013; Gross et al., 2013; Shirzad and Van der Loos, 2013). Advances in machine learning and deep learning have led to disruptive innovations in radiology, pathology, genomics, and other fields (Ramesh et al., 2004; MacEachern and Forkert, 2021). However, modern machine learning models require millions of parameters that need to be learned from sufficiently large, curated datasets to achieve clinical-grade accuracy while being safe, fair, equitable, and generalizing well to unseen data (Althnian et al., 2021; Varoquaux and Cheplygina, 2022). The issue here is how to address the problem of data governance and privacy by training algorithms collaboratively without exchanging the data itself. Rieke et al. (2020) proposed the approach of federated learning, which enables multiple parties to train collaboratively without the need to exchange or centralize data sets. Indeed, the machine learning processing occurs locally at each participating institution and only model characteristics are transferred. Concerning rehabilitation for PwMS, this approach has the potential to drastically increase sample size and enable a broader knowledge and an autonomous approach to the most correct practice to deal with the wide variety of symptoms of PwMS.

2.4.3 The rapid surge of interest in home rehabilitation due to COVID-19

In the last decades, the demand for rehabilitation services has increased due to the aging phenomenon and the prevalence of chronic diseases, but it has faced a shortage of rehabilitation professionals and other barriers, such as low incomes, that deny access to rehabilitation services (Martinez-Martin and Cazorla, 2019). However, the continuity of exercises is crucial for the success of physical therapy and rehabilitation in PwMS, and the recommendation is to continue treatment practices in a home environment to support and maintain functional development in PwMS. Actually, at-home rehabilitation is suitable both for those requiring minor assistance and for those who cannot commute regularly to the treatment in physical therapy centers (Mayetin and Kucuk, 2022). Home-based rehabilitation has been found to be an effective alternative to traditional rehabilitation programs for stroke patients: it can be personalized and adjusted to the patient's needs, can provide a more convenient and cost-effective therapy option (Catalan et al., 2018), achievable in a comfortable setting (Akbari et al., 2021). Additionally, unlike traditional exercises, where accountability relies on self-reporting, robotics enables objective monitoring, ensuring continuous exercise and program adherence. The COVID-19 pandemic caused an early discharge of existing patients, the suspension of new patients' admissions, and the reduction of activities to decrease contacts (Manjunatha et al., 2021). Thus, the easiness of use and the low maintenance needed by haptic devices, together with the emerged necessity for further deploying the power of the internet for the purpose of communication and big data analysis, have attracted a lot of attention for home-based rehabilitation (Akbari et al., 2021). In particular, the need for effective home rehabilitation has received a boost from the need for early rehabilitative treatment to reduce long-term consequences in post-stroke patients (Akbari et al., 2021). Additionally, although many rehabilitation devices including robots are not available to be used at home due to their high costs, recent research has focused on low-cost devices able to assure both safety and effective results, in turn of a simpler design and functioning (Dowling et al., 2014; Rudd et al., 2019; Lambelet et al., 2020). The rehabilitation program for PwMS typically involves several sessions spread over a period of weeks or months. However, individuals with motor disabilities and limited mobility may face difficulties and expenses in traveling to health centers for treatment, which can pose a challenge in accessing rehabilitation services (Zasadzka et al., 2021). Even if this situation has been further complicated by COVID-19, the scenario might evolve into an opportunity for PwMS, as it happened for post-stroke patients. The future perspective is for an increase in the research interest in low-cost and easy-to-use robotic devices and in robot-based protocols for home-based rehabilitation in PwMS.

2.5 Threats

2.5.1 Safety issues when dealing with spasticity

Spasticity is a common symptom in PwMS, characterized by an increase in the resistance of the joint to movement. This increased resistance is dependent on the velocity and caused by an amplification of the stretch reflex during the passive stretching of the joints (Trompetto et al., 2014). Therapeutic exercise treatments for individuals with high levels of spasticity can be challenging for therapists due to the patients' considerable stiffness (Bohannon and Smith, 1987). This can create a barrier to the provision of sufficient rehabilitation therapy (Lee et al., 2017). Although most studies on robot-based rehabilitation in PwMS exclude individuals with spasticity (Carpinella et al., 2009; Sampson et al., 2016; Manuli et al., 2020b; Solaro et al., 2020), robots should be capable of addressing spasticity in a safe and appropriate manner. The proposed methods involve setting an appropriate torque range to manage spasticity-induced resistance or pausing movement when the resistance surpasses the motor's threshold (Nam et al., 2017). The spastic muscle remains active for a certain amount of time with exponential decay of the resistance torque at the end of the range of motion where the robot is actuated against spasticity. This phenomenon allows the robot to be applied to a spastic limb even with a low-torque output motor without causing excessive loading. However, more precise sensing and control systems are necessary to deal safely with this symptom during PwMS rehabilitation.

2.5.2 Risks related to unsupervised therapy

Robot-based rehabilitation is not meant to replace traditional therapies, but rather to complement them (Li et al., 2021). Robotic systems are ideal for providing intensive, task-oriented motor training for patients' limbs under the supervision of a therapist, and are part of a suite of rehabilitation tools that includes nonrobotic methods (Harwin et al., 2006). However, the need to use healthcare resources efficiently is increasing, and there are proposals to enhance the cost-effectiveness of rehabilitation programs, including hospitals, care homes, and home-based rehabilitation (Ward et al., 2008). While robot-assisted therapy has typically been supervised by trained personnel, the trend towards home-based and autonomous rehabilitation is driven by the need to reduce staff workload, despite concerns about the deskilling of therapists and doctors (Li et al., 2021). By allowing patients to use robotics unsupervised or semi-supervised, therapists can handle multiple patients simultaneously during robot-assisted therapy sessions or allow them to receive robot-assisted training at home to increase therapy dose and regularity (Rosati et al., 2007; Ranzani et al., 2021). However, safety is a critical issue for minimally-supervised systems as they should be operated without supervision, restricting the role of the rehabilitation team to planning and remote monitoring (Rosati, 2010). Safety requirements necessitate that the robot does not move patients beyond their range of motion, avoids pressure points on fragile skin, and is easy to clean and compliant with infection control policies (Li et al., 2021). Despite concerns about safety and efficacy in the absence of qualified staff, recent research by Ranzani et al. (2021) has shown that a powered robot-assisted therapy device can be safely and intuitively used with minimal supervision by chronic stroke patients, while still meeting usability and perceived workload requirements. Interestingly, the study found that usability was inversely related to age but not to the level of impairment, with the oldest subjects experiencing the worst usability results (Ranzani et al., 2021). Given the high-dose therapy needed by PwMS, this population would definitely benefit from the increased dose and the continuum of care coming from home-based and autonomous rehabilitation, which could progressively increase patients' involvement and autonomy from the clinic to home. While the potential for unsupervised therapies to complement conventional therapies in real-world settings is significant, safety and efficacy issues still need to be addressed to employ robotic devices with minimal supervision.

3 Virtual and extended reality in rehabilitation for PwMS

Previous sections listed the fields of a SWOT analysis for robotic rehabilitation systems tailored for PwMS. However, strengths can be empowered, opportunities can be exploited, weaknesses can be overcome, and threats can be prevented. Pondering the potential synergies of robotic devices with different technologies (as in the larger framework of Digital Health), virtual and augmented environments offer fertile solutions (De Angelis et al., 2021; Scholz et al., 2021; Kanzler et al., 2022a; Kanzler et al., 2022b; Chan et al., 2023).

3.1 Introduction to virtual and extended reality

Virtual Reality (VR) technologies can generate varying levels of immersion, defined as the sensation of being fully surrounded by a digital environment (Gandhi and Patel, 2018). Head-Mounted Displays (HMD) are typically used for full immersion, while large screens and projectors achieve semi-immersion, and simple monitors provide non-immersive VR experiences, even in common video games. At a psychological level, immersion can contribute to presence, the sensation of sharing time and space with another agent, object, or event through a medium. These processes, also enhanced through systems for haptic feedback and control, generally contribute to making the experience of a VR system engaging, especially when it is enriched by game-based features (Moline, 1997; Schuemie et al., 2001; Vafadar, 2013; Stone et al., 2014; Menin et al., 2018; Rose et al., 2018; Elor et al., 2020; Lee et al., 2020). However, VR constitutes just one category within a spectrum of environments, ranging from fully digital to entirely real, with some experiences involving no technological mediation in individual interactions. Originally, Milgram et al. (1995) defined the region between reality and VR as Mixed Reality (MR) to encompass all types of combinations of real and digital items. Within the sub-continuum of MR, Augmented Reality (AR) embraced the cases where digital items were perceptually inserted in a real scene, and Augmented Virtuality (AV) considered the situations where real objects enriched a digital setting. Additionally, different sub-types of AR emerged: overlay AR shows digital objects just floating in the visual scene, dissociated from the real context; encrusted AR represents digital objects visually behaving as real ones (they can be placed on a surface or they fall according to the law of gravity). An interesting case is the one of Spatial Augmented Reality (SAR) (Khademi et al., 2013), where the real environment is not augmented through a visor worn by a user but directly on its surfaces by means of screens or projectors. However, a debate on the meaning of such labels currently proceeds, leading to the adoption of the term Extended Reality (XR) as the set of combinations of digital and physical items and interactions (Stone, 2020). In all cases, the role of the digital items is to increase the information and the control opportunities offered by a User Interface (UI) or, specifically, a Graphical User Interface (GUI) (Carmigniani and Furht, 2011; Ejaz et al., 2019; Condino et al., 2022; Fu et al., 2022).

3.2 Virtual and extended environments for PwMS

Considering both virtual and augmented contexts, technologies represent a promising avenue for rehabilitation interventions. Indeed, they offer immersive and interactive experiences that enhance patient motivation and treatment outcomes (Khademi et al., 2013; Regenbrecht et al., 2014; Mubin et al., 2019; Sánchez-Herrera-Baeza et al., 2020; Leong et al., 2022; Araujo et al., 2023), including cases of MS (Massetti et al., 2016; Jonsdottir et al., 2019; Kalron et al., 2022; 2020; Cuesta-Gómez et al., 2020; Chadali et al., 2023; Milewska-Jędrzejczak and Głąbiński, 2023). Indeed, VR and AR environments have proven to encourage neuroplasticity in neurological patients in terms of learning abilities and verbal short-term memories, as well as improve fatigue and quality of life (Huang et al., 2022; Araujo et al., 2023; Milewska-Jędrzejczak and Głąbiński, 2023). It must also be noted how, due to its impact on their vestibular systems, VR seems to have specific effects on PwMS, altering their sense of presence and even leading to discomfort and cybersickness in immersive environments. This observation highlights the need for designing multimodal feedback solutions to enhance the accessibility of interactive settings (Guo and Quarles, 2012; Samaraweera et al., 2015; Arafat et al., 2016; Mahmud et al., 2023; 2022; Hollywood et al., 2022). In a study conducted on 54 PwMS undergoing a 12-week VR-based rehabilitative intervention, Saladino et al. (2023) showed the effectiveness of such an approach in improving abilities in performing activities of daily living, quality of life, and satisfaction throughout the therapeutic sessions. Overall, it is worth highlighting that when comparing VR *versus* XR technologies in rehabilitation, the latter sees way less employment with respect to the first one (Mubin et al., 2019). A rare example is the study of Pruszyńska et al. (2022) which assessed the effects of applying AR in telerehabilitation for PwMS over a 4-week experimental study. Although no particular difference has been found in neuroplasticity between AR and conventional therapy groups, a significant decrease in task execution time and an increase in grip strength with respect to the control group was noted in both arms.

Furthermore, through the use of serious games (games devised for non-leisure applications too, from education to therapy) and the approach of gamification (adding game features to non-leisure systems), the patient is led to perform repetitive training activities with higher motivation and, consequently, clinical adherence (Godfrey and Barresi, 2022). VR-based exergames have garnered attention within MS rehabilitation, particularly for targeting upper limb movements (Webster et al., 2021; Pau et al., 2023b; Chadali et al., 2023). These games combine task-oriented exercises with elements of gamification to create engaging rehabilitation experiences (Jonsdottir et al., 2019). They offer diverse exercise scenarios, allowing customization based on individual patient requirements and variations in symptoms (Leocani et al., 2007). Additionally, they can offer options for patients who could refuse fully immersive settings or excessively playful ones. VR/XR exergames can provide real-time feedback and visual cues, enhancing patient immersion and performance (Hsu et al., 2023) and serving as tools for self-guidance and self-evaluation

(Sousa et al., 2016; Bucchieri et al., 2022). Indeed, it has been shown that providing appropriate feedback to the user is crucial to enhance movement correctness, directly linked to therapy effectiveness (Cavalcante Neto et al., 2020). However, it is worth noting that many studies in the literature rely on commercially available exergames, which are often not customizable (Webster et al., 2021).

Virtual settings can offer an immersive experience and a sensation of presence to empower the individual motivation in repetitive tasks that can be psychologically and physically tiresome even if the patient interacts with a robotic device (Tang et al., 2005; Clark et al., 2019). On the other hand, different from robotic rehabilitative systems present in clinics, VR/XR devices represent an optimal solution for home-based rehabilitation. Cost-effective and easy to set up, they can provide useful settings for occupational therapy (Corrêa et al., 2013; Pruszyńska et al., 2022; Tada et al., 2022). An example is the immersive virtual kitchen game proposed by Pau et al. (2023a) where the environment provides several activities of daily living tasks (e.g., tidying up, cooking, washing the dishes, *etc.*). Questionnaires conducted on an 8-week study on PwMS showed overall great appreciation and satisfaction with the proposed rehabilitative environment.

Another aspect of such systems is the presence of refined sensors to collect kinematic measurements (i.e., upper-limb and ocular movements) and quantify the quality of patients' recovery (Leocani et al., 2007; Pillai et al., 2022; Tada et al., 2022; Herrera et al., 2023). Soares et al. (2021) evaluated the hand tracking accuracy of HTC Vive (immersive VR headset) and HoloLens2 (XR headset) with respect to a Motion Capture (MoCap) system, while Pascucci et al. (2022) and Pillai et al. (2022) compared the use of a Microsoft Kinect-based prototype and HoloLens2. These studies revealed the suitability of VR and XR headsets to detect jerky behavior in kinematic data and unexpected hand movements, and to precisely evaluate movement tracking. Nonetheless, with such devices, it might be possible to perform accurate rehabilitative assessments and evaluate motor dysfunctions in PwMS (Herrera et al., 2023). Although such a feature might appear redundant when using a robotic system, the data obtained through VR/XR devices can be integrated with the information collected by the robotic platforms. This integration creates a more comprehensive and enriched portfolio of the therapeutic journey, enhancing the overall experience and outcomes.

4 Robotic and VR integration for MS rehabilitation

4.1 Mechatronic-digital synergies

In this manuscript, we analyzed how robot-assisted rehabilitation for PwMS has the potential to represent a significant advancement. Additionally, especially when integrated with virtual or augmented environments, this approach can offer an even more patient-centric solution that goes beyond the limitations of standard care.

Previous studies have emphasized the potential of combining robotic and digital technologies for rehabilitation, highlighting the benefits of synergistic strategies. Patton et al. (2006a) remarked how the flexibility of both approaches can offer promising solutions for cost-effective, time-efficient, and repetitive exercises for neurological (specifically, brain-injured) patients. These solutions exploit our knowledge of the nervous system with the versatility of virtual/augmented settings and the accuracy and precision of robots, opening up exciting possibilities. Achieving success in this field depends on the active involvement of therapists and clinicians in the co-design process, as well as the state-of-the-art in haptic and graphic systems. The latter point is particularly interesting, as demonstrated by recent studies by Atashzar et al. (2019), highlighting the need for matching the patients' needs and biomechanics, the stability in physical patient-robot interaction with a high level of fidelity of force field, the chance of implementing home solutions for improving clinical outcomes while reducing adoption costs.

Overall, the debate on VR-enhanced motor-cognitive rehabilitation robotics (Riener et al., 2006) always focused on the capability of multimodal displays to make therapy more exciting and increase patient engagement. Indeed, visuo-haptic approaches derived from the synergy of digital and mechatronic solutions were definitely impactful for engaging subjects through "reality distortion", by using error augmentation strategies (Patton et al., 2006b). Mutually, the haptic properties in human-robot interaction can enrich visual digital items with tactile features that raise up user engagement (D'Antonio et al., 2021; Frisoli et al., 2009; Gueye et al., 2021; Li et al., 2014; Ruffaldi et al., 2014). These were just exemplary studies on the documented principles underlying the synergies of virtual and robotic systems in rehabilitation, and the literature reveals an even richer set of investigations in this area (Qiu et al., 2010; Guidali et al., 2011; Merians et al., 2011; Cortés et al., 2014; Russo et al., 2018; Mubin et al., 2019; Manuli et al., 2020a; Torrisi et al., 2021).

Notably, Zanatta et al., 2023a, Zanatta et al., 2023b, Zanatta et al., 2022) explored the potential of combining robotic and virtual systems in rehabilitation, by analyzing their practical implications. The authors proposed a biopsychological approach to examine the points of view offered by multiple health-related perspectives, according to diverse technological solutions and heterogeneous conditions. Through such a vision, especially useful in Health Technology Assessment (HTA), they addressed public health challenges and healthcare sustainability for evaluating the introduction of the aforementioned integration of digital and mechatronic systems in rehabilitation. In particular, addressing the limitations reported by patients is essential. Patients generally reported high levels of acceptance, satisfaction, and perceived safety during treatments involving the combined use of these technologies. Nevertheless, the authors emphasized the need for in-depth advances in terms of assessment: the next subsection proposes an approach for handling this challenge, with a special focus on the context of PwMS upper-limb rehabilitation.

4.2 Towards an integrative SWOT analysis

To develop a comprehensive and fully functional rehabilitation platform beneficial for PwMS, the two technological domains of

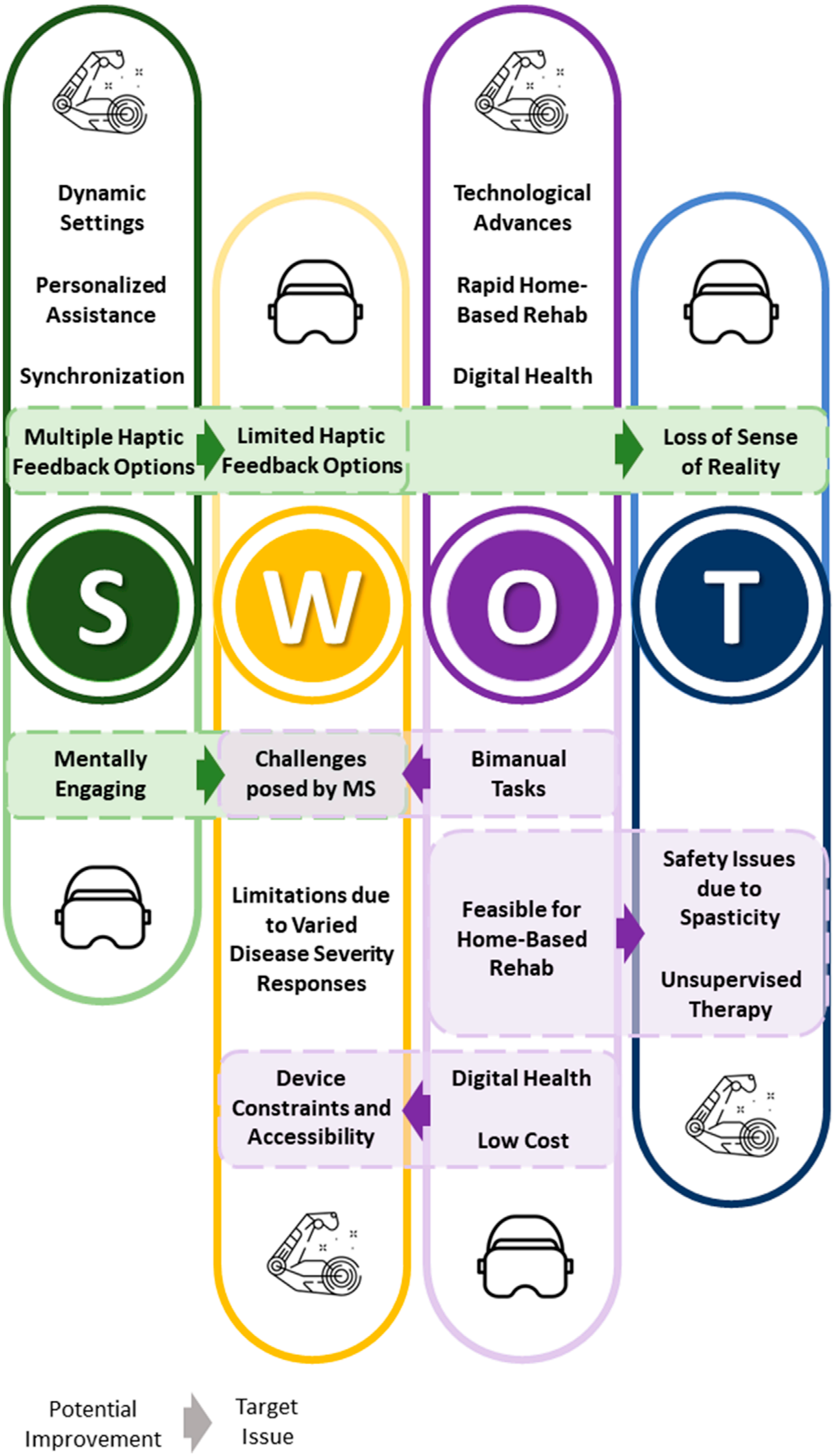

FIGURE 2
This figure summarizes a unified SWOT analysis for robotics and VR, along with their interrelated elements. Dashed boxes contain strengths or opportunities of VR that can help overcome the weaknesses and threats of robotic devices, and *vice versa* as discussed in Section 4. The direction of the arrows indicates which potential improvement (stemming from strengths or opportunities) of VR or robotic devices could address a target issue (weakness or threat) of the other technology.

robotics and virtual/extended reality must address their respective weaknesses while leveraging their strengths in rehabilitation. Utilizing embedded sensors, robots and VR/XR technology can create dynamic environments that promote sensorimotor restoration. For example, headsets can immerse individuals in a digital world, enabling them to engage in tasks closely resembling real-life challenges. However, interacting solely with virtual objects may lead to a loss of the sense of reality. Robotic devices, on the other hand, can provide haptic feedback and generate a strong sense of involvement in the task. For instance, the use of devices like the Haptic Master in conjunction with task-specific and engaging non-immersive virtual environments, such as the I-TRAVLE system (Maris et al., 2018), has demonstrated promising results in PwMS rehabilitation.

Selecting the appropriate rehabilitative strategy becomes particularly challenging when dealing with neurological disorders. PwMS often exhibit unique symptoms, leading to the need for optimal robotic control strategies and visual stimuli to provide personalized assistance. From a kinematic impairment perspective, PwMS may experience varying degrees of disability in both arms, with the more affected side not necessarily corresponding to the dominant one. However, given the main focus of the researchers on stroke-related impairments, the majority of upper-limb exoskeletons are designed for unilateral use. To address this limitation, immersive VR/XR technologies can promote bi-manual exercises and accurately measure the user's hand movements in the non-treated arm, creating a comprehensive digital representation of the patient. This clinical portfolio can provide valuable quantitative data for monitoring the rehabilitation progress and training predictive AI models. Alternatively, when dealing with cognitive impairments, VR/XR environments can be simplified to make tasks more accessible and easier to understand or enriched with challenging mental exercises to enhance neuroplasticity.

VR systems, characterized by their ease of access and cost-effectiveness, present also an attractive option for home-based rehabilitation, complementing clinic-based robotic interventions and assuring the continuum of care needed by PwMS. In cases of relapse or hospitalization, robot-assisted rehabilitation often takes precedence. During this phase, patients may require passive movement, extensive assistance, and gravity compensation, which can be facilitated through robotic devices. However, once this phase concludes, the challenge lies in the paucity of robotic devices suitable for home-based rehabilitation. To ensure continuous rehabilitation and patient monitoring, VR systems, enhanced by computer vision techniques, can be employed by patients in their own homes. This combination allows patients to continue their rehabilitation at home, preventing issues like de-conditioning, muscle weakness due to limited mobility, and muscle contractures associated with spasticity. This synergy offers a holistic approach that keeps patients trained, engaged, and tracked in their recovery journey. This synergistic approach fosters a comprehensive strategy that not only keeps patients actively engaged but also facilitates effective tracking throughout their recovery journey. Importantly, relying on VR for home-based rehabilitation carries fewer risks associated with unsupervised therapy. While VR-based rehabilitation encourages active movements, its limitation in haptic feedback diminishes potential adverse effects, thereby enhancing safety during unsupervised sessions. This innovative integration not only propels the efficacy of home-based rehabilitation but also underscores a commitment to patient wellbeing and progress.

Figure 2 provides a holistic overview of a comprehensive SWOT analysis that includes both robotics and VR. This visual representation illustrates how the advantages of each of these two innovative technologies can be exploited to complement each other and overcome their respective limitations. To sum up, considering the SWOT analysis of robotic systems performed above, the synergy with virtual and augmented environments can:

- Enhance the strengths observed about dynamic environments (generating engaging contents), haptic feedback (through its visual and multimodal counterparts), personalized assistance (stimulating the person with a novel game-like scenario for the same robot-based task when the user is tired, as in the Cypress approach);
- Mitigate the weaknesses in accessibility by presenting an ecologically valid and intuitive setting for rehabilitation, and the weaknesses related to the challenges posed by MS by creating a more comprehensive digital representation of the patient;
- Develop the opportunities offered by Digital Health and telerehabilitation, especially considering how low-cost technologies for VR and XR are proposed at a high pace on the market;
- Prevent the safety issues related to the rise of unpredictable symptoms (e.g., spasticity) and the possible consequent threats during unsupervised therapy.

5 Conclusion

Our review focused on the use of robotic systems in the context of Multiple Sclerosis rehabilitation, with a particular emphasis on conducting a SWOT analysis of these systems. Our comprehensive goal was to assess whether the synergy with other systems, in this case virtual and extended reality (VR/XR) technologies, could enhance the Strengths, mitigate the Weaknesses, explore new Opportunities, and address the Threats of rehabilitation robotics for MS. We found that both robotic systems and VR/XR technologies exhibit distinct advantages and disadvantages. Some of these limitations cannot be entirely overcome by combining the two technologies, yet there are clear areas where their synergy can be highly beneficial. Although providing haptic feedback through robotic devices remains critical especially when MS symptoms are severe, the incorporation of VR systems, offers clear advantages for home-based rehabilitation, aligning with the growing need for a continuum of care in the management of MS. Moreover, the integration of VR/XR technologies can enhance engagement and realism in rehabilitation tasks, making them more closely resemble activities of daily living (ADL). It is noteworthy that we chose to primarily focus on VR/XR technologies due to their widespread use, simplicity, and ease of integration into the existing healthcare landscape. While other technologies, such as Functional Electrical Stimulation (FES) or EEG-based brain–computer interfaces (Said et al., 2022), hold promise, we believe that starting with VR is a pragmatic approach given its established presence and adaptability within the current context. In summary, our analysis provides an in-depth perspective on the current framework within which robotic technologies are integrated into Multiple Sclerosis MS rehabilitation. Moreover, it underscores the transformative impact of merging robotic systems with VR technologies, shedding light on their individual strengths and areas for enhancement. This synthesis paves the way for a promising future, aiming to deliver more effective and accessible rehabilitation solutions for individuals facing the challenges of MS.

Author contributions

GA: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. AB: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. JP: Writing–review and editing. AT: Writing–review and editing. SB: Writing–review and editing. ED: Writing–review and editing. ML: Writing–review and editing. KM: Writing–review and editing. MH: Writing–review and editing. JZ: Conceptualization, Writing–review and editing. LD: Writing–review and editing. GBr: Writing–review and editing. GBa: Conceptualization, Investigation, Supervision, Writing–original draft, Writing–review and editing.

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Conflict of interest

GA and JZ were employed by ReWing s r l.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Use of an upright power wheelchair in spinal cord injury: a case series

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Objective: To explore independence, usability, and self-reported quality of life (QOL) in eligible persons with spinal cord injury (SCI) who used a standing powered wheelchair over a 12-week period. Setting: VA SCI research facility.
Participants: Four participants with chronic SCI who use a wheelchair as the primary means of mobility.
Intervention: A standing power wheelchair was used three times a week (3.5 h/session) for 12 weeks in a supervised setting. Main Outcome Measures: safety, usability and feasibility, blood pressure in seated and standing positions, bowel, bladder, and pain item banks from the SCI-QOL Physical-Medical-Health domain, and overall user satisfaction with the device.
Results: Participants consistently maintained normal blood pressure responses between seated and standing positions throughout the training sessions and learned to perform all the mobility tasks safely and independently. Participants reported improvements on the SCI-QOL and were generally satisfied with the upright standing power wheelchair.
Conclusions: In this small case series of chronic, non-ambulatory individuals with SCI, the standing powered wheelchair was shown to be safe and efficacious.

KEYWORDS
standing power wheelchair, spinal cord injury, quality of life, usability, safety, tetraplegia, paraplegia

1 Introduction

Approximately 27.2 percent of the US population has some type of disability and about 10 percent have a physical disability resulting in a mobility impairment. Approximately 18.4 million people use various assistive technology devices for mobility and 5.5 million people use a wheelchair (1, 2). Innovative wheelchair technology is integral for users to maintain a mobile lifestyle with enhanced function, increased independence, and greater accessibility in the home, work, and community. As a result, the wheelchair is the primary mobility device for this segment of society. As individuals using wheelchairs adapt to the use of a wheelchair in daily life, it soon becomes an extension of their bodies. Although wheelchairs provide mobility, people with spinal cord injury (SCI) who are non-ambulatory are at risk for many secondary medical consequences due to paralysis and the extreme amount of time spent sitting. The rate of wheelchair usage is increasing has led to a growing demand for better wheelchair solutions.

Reducing the time sitting has become a major goal to improve physical activity. Despite of ergonomic advanced office chairs, typically sitting for more than two hours has been associated with the development of pain (3, 4). As such, frequent standing and/or repositioning is recommended in an ambulatory population who sit for a prolonged period (5, 6). Ambulatory population studies correlate increased sitting with increased body mass index and mortality and reducing the amount of time sitting improves metabolic outcomes (7–9). Similarly, frequent wheelchair position changes are advised (5, 10, 11). While standing has benefits, current wheelchair solutions have limitations. A powered wheelchair (UPnRIDE) offers seated, stationary standing, and overground standing mobility. We tested the safety, useability, and user satisfaction on the UPnRIDE power wheelchair.

Our group has reported that exoskeletal-assisted walking has some positive effect on bowel function (12). Very little has been published on the effects of using a standing wheelchair. In one study by Dunn et al., they reported on usage of the device at one and five years; 84% of responders were using the standing wheelchair to stand, with 41% standing one to six times per week and that 21 of 99 surveyed reported improved bladder control, and a small unspecified number reported better bowel regularity, reduced urinary tract infections, reduced leg spasticity, and reduced bed sores (13). In contrast, Kwok et al., reported in a randomized controlled trial (RCT) that there was no effect from standing on time to first stool (14). We wanted to explore if long-term standing and frequent position changes would have a positive effect on bowel function and other on quality of life outcomes for those with SCI (15, 16).

The goal of this pilot project was to determine the effects of standing with the UPnRIDE powered wheelchair for extended periods of time in a supervised setting on safety, independence, usability, and QOL in eligible persons with SCI who typically spend most of their waking hours sated due to limited access to standing modalities.

2 Methods

2.1 Recruitment and screening

This study was approved by the Institutional Review Board (IRB) of the James J. Peters VA Medical Center (JJPVAMC), Bronx, NY and registered in the clinicaltrials.gov website listing (NCT04163796). The targeted study population was individuals with chronic SCI (≥6 months) who were non-ambulatory and therefore used a wheelchair for the primary mobility. The study SCI staff physician was the primary source for identifying potential participants. Additionally, IRB-approved flyers and brochures were distributed. Potential participants were informed about the details and eligibility for the study and given the opportunity to ask question before signing the informed consent. Consented participants were screened by a history and physical examination incorporating the following: the International Standards for Neurological Classification of SCI (ISNCSCI) examination to determine the level and completeness of injury; range of motion at the hips, knees and ankles bilaterally; and orthostatic tolerance test.

Patients with autonomic dysreflexia (AD) and/or frequent orthostatic hypotension (OH) are potentially those who may benefit the most from regular upright posture. These patients were not excluded because we have learned from our Exoskeleton Assisted Walking (EAW) studies that by titrating their time in a standing position, people with those conditions can adjust to tolerate upright posture with strict monitoring of blood pressure (BP) and symptoms. BP for adverse changes and clinical symptoms were frequently monitored during all sessions. If a systolic BP decrease of greater than or equal to 20 mmHg or a diastolic BP decreased of more than 10 mmHg occurred within 3 min of changing position and/or the participant was symptomatic, we immediately bought the individual back to sitting or a horizontal position. Additionally, if there was a trend towards and fall in BP or any mild symptoms presented, they were encouraged to return to a seated position. Any changes in BP were listed as expected risks in the protocol and in the consent form and did not warrant an Adverse Event report unless they remained unresolved with sitting or supine, which never occurred, because the BP reductions and symptoms all resolved with sitting and the participant went on to tolerate standing.

To rule out participants who may be at high risk for a fragility fracture from weight bearing during standing in the wheelchair, a bone mineral density (BMD) scan was performed on the bilateral knees (proximal tibia and distal femur) as well as the dual femur (femoral neck and trochanter) using Dual Energy x-ray Absorptiometry (DXA). In addition, individuals with other bone conditions indicative of a high risk of fracture were excluded at the discretion of the study physician's clinical judgement. The complete list of inclusion/exclusion criteria is described below (Table 1).

2.2 Research design

An open-label, single group perspective pre- and post-intervention study was conducted using a convenience sample.

TABLE 1 Enrollment criteria.

Enrollment criteria
Inclusion criteria
1. Use a wheelchair as a primary means of mobility;
2. Males and females, between 18 and 65 years old;
3. Traumatic or non-traumatic tetraplegia or paraplegia >6 months in duration;
4. Height 160 cm–190 cm (63–75 in or 5'3"–6'3" ft);
5. Weight <100 kg (<220 lb);
6. Able to sign informed consent.
Exclusion criteria
1. Able to ambulate with or without an assistive device or physical assistance greater than 4 consecutive steps;
2. Any pressure ulcer at any location that is deemed to be contraindicated for a power wheelchair or standing frame by the study physician;
3. Concurrent medical disease that would be exclusionary for standing (as per the clinical judgment of the study physician);
4. Severe spasticity (Ashworth 4) or uncontrolled clonus;
5. History of fragility fractures, long bone fractures in the past 1 years, heterotrophic ossification, or other bone conditions that would be exclusionary for use of a standing modality as per the clinical judgement of the study physician;
6. Significant contractures that would be exclusionary for use of a standing modality as per the clinical judgement of the study physician;
7. Psychiatric or cognitive status that may interfere with the ability to follow instruction to use the device; and
8. Pregnant or lactating women.

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FIGURE 1
The UPnRIDE powered wheelchair. Image depicts the seated (Left) and standing position (Right) of the wheelchair.

The intervention consisted of approximately 3.5-hour sessions, 3 times per week over 12 weeks.

2.3 Device features and description

The UPnRIDE powered wheelchair can change position from sitting to standing and standing to sitting or can be extended to a full supine position and can be used for indoor and outdoor mobility (Figure 1). The device is operated by the user with a joystick and a main computer controller and includes a driving motorized module, standing and sitting module, and stabilization module which can be adjusted and corrected to an upright position up to 7° while standing and 12° while sitting.

2.4 Training sessions

During the first session, the participants were fitted in the device and given instructions about transferring (with assistance when needed) in and out of the wheelchair, taught how to control the position functions, and the wheelchair mobility skills (17). Participants were asked to use the UPnRIDE three times per week for 12 weeks. Sessions lasted, on average 3.5 h, during which participants spent time in the UPnRIDE as well as the transfer in and out of the wheelchair. Participants were encouraged to use the wheelchair for 3–4 h per session, but times would vary based on when their transportation dropped them off or picked them up. During each 3.5-hour session, participants were asked to stand at least 5 min during every 15 min or more as tolerated to determine their tolerance level without causing any undue problems from standing, such as blood pooling in the lower extremities, lightheadedness, or other discomforts. The recommended standing time for the participants was based on their individual health status and level of injury, but mostly their self-reported tolerance to standing. Tolerance depended on a few factors including participant comfort and stability of their blood pressure. In the first few sessions adjustments were made to the wheelchair to increase user comfort. This included options such as changing the angle of the standing position, tightening, loosening, or swapping the straps for better comfort and supporting the user to the back of the chair. If blood pressure continued to decrease for a few minutes after standing or symptoms of orthostatic intolerance presented, the participant was returned to a sitting position. Typically, standing time was tolerated for a few minutes during the first few sessions and increased gradually over time.

Heart rate (HR), blood pressure (BP), total session time, time in standing position, count of sit-to-stand positioning changes, total distance of overground movement, and comfort scale (0 = N/A, 1 = Very Uncomfortable to 5 = Very Comfortable) were monitored during each session. Participants used the UPnRIDE on the hospital floors in the hallways and outside on the hospital grounds. The hospital grounds provided a variety of conditions that the participants could use the wheelchair such as ADA compliant ramps, curb cut-outs, side slopes, and grass (soft surface). In addition, the participants were encouraged to use the chair as they would in everyday circumstances. These tasks ranged from preparing food, reaching cabinets, transferring, playing card games, using a computer, and riding elevators. One subject took the UPnRIDE on a bus to a fast-food restaurant to pick up lunch. At all times during a session at least one member of the study staff was with the participants. This was a safety requirement by our IRB in the event of equipment malfunction. However, very little assistance was needed by the study team member during these activities. Vital signs were taken whenever a participant changed position. If a participant experienced any blood pressure instability, appropriate positioning was performed, and vital signs were monitored as frequently as once a minute.

2.5 Outcome measures

The primary outcomes were safety (number, relatedness, and severity of adverse events), usability, and feasibility determined from a variety of wheelchair mobility skills and an activities of daily living course. These were performed to assess an individual's functional independence. Blood pressure was measured in the seated and standing positions, and a spinal cord injury quality of life (SCI-QOL) measurement tool for bowel and bladder management difficulties, bladder complications, pain interference and pain behavior were used to determine whether reducing sitting time by a standing intervention had positive changes on these variables. The measurements were performed 3 times: pre- (baseline) and post-testing (after 36 sessions). Following completion of the study, each participant was asked to complete a questionnaire of the overall satisfaction of using the UPnRIDE.

2.5.1 Safety with blood pressure during seated and standing positions

Blood pressure and heart rate (HR) were measure by a vitals monitor (GE Medical CARESCAPE V100 monitor) (18) and were monitored frequently during seated and standing positions for every session.

2.5.2 Usability and feasibility

A modified Wheelchair Skills Test (WST) was used to assess the difficulty level of participants in completing mobility skills while using the UPnRIDE. The grading for the WST for mobility skills with the UPnRIDE was as follows: 0 = fail, 1 = pass with difficulty, and 2 = pass. The original WST is a comprehensive and generic instrument for objectively evaluating wheelchair skills (19). However, since the UPnRIDE is a standing power wheelchair, additional operations of sit-to-stand and stand-to-sit were included in the modified WST.

2.5.3 Quality of life outcomes

The SCI-QOL measurement tools for the physical-medical health domain for bowel and bladder management difficulties, bladder complications, pain interference and pain behavior were performed at the three study time points. Lower scores indicate more positive responses, and a five-point decrease is considered to be a clinically meaningful improvement (20, 21). The SCI-QOL Bowel Management Difficulties SF9a and Bladder Management Difficulties SF8a scales use the following response options: "Not at All (1)," "A Little Bit (2)," "Somewhat (3)," "Quite a Bit (4)," and "Very Much (5)." Meanwhile, the SCI-QOL Bowel Management Complications scale has six questions with response options of "Never (1)," "Rarely (2)," "Sometimes (3)," "Often (4)," and "Always (5)." Regarding Pain, the Pain Behavior scale had 3 questions that were scored as follows: "Never (1)", "Rarely (2)", "Sometimes (3)", "Often (4)", "Always (5)" and 4 questions that were scored as follows: "Had No Pain (1)", "Never (2)", "Rarely (3)", "Sometimes (4)", "Often (5)", "Always (6)". The Pain Interference Short Form had 7 items that were scored as follows: "Not at All (1)", "A Little Bit (2)", "Somewhat (3)", "Quite a Bit (4)", "Very Much (5)" and 3 questions that were scored as follows: "Never (1)", "Rarely (2)", "Sometimes (3)", "Often (4)", "Always (5)".

2.5.4 Overall satisfaction

An Overall Satisfaction questionnaire was designed to measure participants' reactions to using the UPnRIDE. The questionnaire used a 5-point Likert scale (1 = Very Poor, 2 = Poor, 3 = Moderate, 4 = Good, 5 = Very Good). Participants were asked to rate their ability to adjust the device's position when performing certain activities. Ratings greater than three are favorable responses. Participants were also asked what they liked most and least about the UPnRIDE wheelchair based on their experience using an open response.

2.6 Data analysis

Since the sample size of this pilot study was small ($N = 4$), each participant's data is reported as a case series. The continuous variables were reported in mean plus or minus standard deviation (SD) for each individual. Total standing time over 36 sessions and the average number of times changing position were calculated and reported as mean ± SD to determine each of the participants' overall performance during this study.

TABLE 2 Demographic information.

ID	P1	P2	P3	P4
Age (Years)	54	56	45	41
Height (m)	1.7	1.72	1.63	1.75
Weight (kg)	89	74	100	79
BMI (kg/m^2)	26.15	21.51	30.67	22.68
Sex	Male	Male	Female	Male
Duration of injury (Years)	31	31	3	5
LOI - AIS classification	C5 - AIS A	C4 - AIS D	T4 - AIS C	T6 - AIS A
UEMS right	16	22	25	25
UEMS left	14	25	25	25
LEMS right	0	8	1	0
LEMS left	0	8	0	0

P1-P4, Participant and number; M, meters; KG, kilograms; LOI, level of injury; AIS, American spinal injury association impairment scale; UEMS, upper extremity motor score; LEMS, lower extremity motor score.

3 Results

3.1 Participants

A total of seven participants were enrolled between 15 November 2018 and 13 March 2020. Four participants had completed 36 sessions when in-person research visits were not permitted due to the COVID-19 pandemic. After 18 months of study closure, loss of funding did not permit the re-start of the study. Therefore, we are reporting on the four participants who completed the 36 sessions as a case series. Any missed sessions (due to weather, transportation, etc.) were added on to the length of the training period, when possible, to achieve a total of 36 sessions The average length of the training period took three to four months to complete the total sessions. Demographic information for gender, height, weight, duration of injury, level of injury, and ISNCSCI classification are listed (Table 2).

3.2 Safety

There were no study-related serious adverse events (SAE) or adverse events (AE) that occurred during the use of the device or while the four participants were enrolled in the study. The four participants had appropriate HR and BP responses throughout the training sessions. HR and BP are two crucial physiological parameters that can be affected by changes in position, particularly in those with SCI who may experience sudden falls in BP, it is notable that none of the participants experienced a decrease of at least 20 mmHg in systolic blood pressure or a decreased of at least 10 mmHg in diastolic blood pressure within 3 min of changing from a supine to a sitting position (22). If a participant's blood pressure had a decrease or they had symptoms, they were encouraged to return to a seated position. These changes in BP were listed as expected risks in the protocol and consent form and did not warrant an Adverse Event report unless they remained unresolved with sitting, which never occurred, because the BP reductions and symptoms resolved with sitting and the participant went on to tolerate standing.

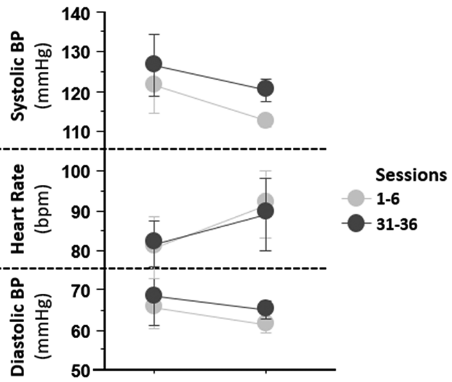

FIGURE 2
Hemodynamic results by session block from the first (1–6) and last 6 (31–36) sessions. Average systolic and diastolic blood pressures and heart rates are reported on the *y*-axis. On the *x*-axis are session block. The graph presents decreasing diastolic BP and systolic BP, increasing heart rate during seated and standing positions from the first to the last, and BP was well tolerated over all sessions.

There were no HR or BP-related AEs while using the UPnRIDE, though in the early sessions 2 of the participants had lower BP and were brought to a seated position as a precaution.

Overall, participants had appropriate HR and BP responses throughout the training sessions (Figure 2). Systolic and diastolic blood pressures decreased with standing. HR increased with standing, all within the expected range.

3.3 Usability and feasibility

Participants learned to independently perform the mobility tasks of sit-to-stand and stand-to-sit, over smooth and various ground surfaces while in the upright standing position and to navigate the activities of daily living course (ADLC). The individual skills to operate the battery charger and engage/disengage the motors require fine motor skills of the upper extremities. As such, participants with limited hand function had difficulty operating the battery charger and engaging and disengaging the motors. Therefore, research trainers assisted operation of the charging cable. However, controlling a joystick and pushing buttons to adjust positions was possible using the wrists. The participant-reported comfort scales with performing mobility skills during training were 4 = Comfortable or 5 = Very Comfortable. During the 3.5-hour sessions over 12 weeks, all four participants were able tolerate more standing time than siting time. Because of the design of the device, the leg rests created a barrier between wheelchairs, and participants found it challenging to transfer in and out of the UPnRIDE wheelchair. Transferring required effort and time for the development of specific strategies (Table 3).

TABLE 3 Usage of UPnRIDE wheelchair.

ID	P1	P2	P3	P4
Average standing time per session (minutes)	95.6	89.8	90.2	147.9
Average sitting time per session (minutes)	63.7	75.3	22.6	27
Completion time (days)	126	105	130	105

P1-P4, participant and number. P1 is missing standing and sitting times from a datalogger malfunction. However, the times were estimated from session start/end time, since P1 was asked to change positions every 15 min. The average duration that participants spent using the device was 182 min. The minimum amount of time recorded was 67 min, while the maximum duration was 324 min.

3.4 Bowel, bladder and pain item banks from the physical-medical-health domain of the SCI-QOL

The results from the SCI-QOL Physical-Medical Health domain for bowel and bladder management difficulties, bladder complications, pain behavior, and pain interference are reported (Figure 3). P1 reported bladder management difficulties were complicated after using UPnRIDE. Other categories stayed the same before and after using UPnRIDE for this individual. P2 reported improvements on bowel and bladder management, but the other outcomes stayed the same. P3 reported improvement on bowel management but had more difficulties with bladder management. Lastly, P4 reported worsening bowel management but reported improvements on bladder management and reduced bladder complications, pain interference, and pain behavior.

3.5 Overall satisfaction

Participants were generally satisfied with the UPnRIDE wheelchair (Mode = 5: Very Good), receiving positive responses for support, stability, reclined position while resting, and stability of standing position. The ratings from participants for ease of transferring, stability of adjusting, and comfort of adjusting were moderate. The individual specific feedback for overall satisfaction is reported (Table 4).

4 Discussion

In this pilot safety, feasibility, and useability study, it was demonstrated that the four participants could independently perform the mobility tasks of sit-to-stand and stand-to-sit as well as maneuver the wheelchair over multiple ground surfaces while in the upright standing position. The participants were able to spend more time standing than sitting. The participants reported overall satisfaction of "good" with the device. Using a standing power wheelchair three times per week for 12 weeks was beneficial to increase BP tolerance with changing position. Results from the BP between seated position and standing position showed all participants were able to tolerate changing positions. Since there is no consistently effective single treatment for orthostatic hypotension (OH) in SCI, combining and individualizing management could provide OH tolerance (23–25). A couple of practical nonpharmacologic treatments to minimize hypotensive effects such as adjusting activity time and position adjustment were done with using the UPnRIDE. Therefore, using the standing power wheelchair was beneficial for a progressive tolerance to upright posture.

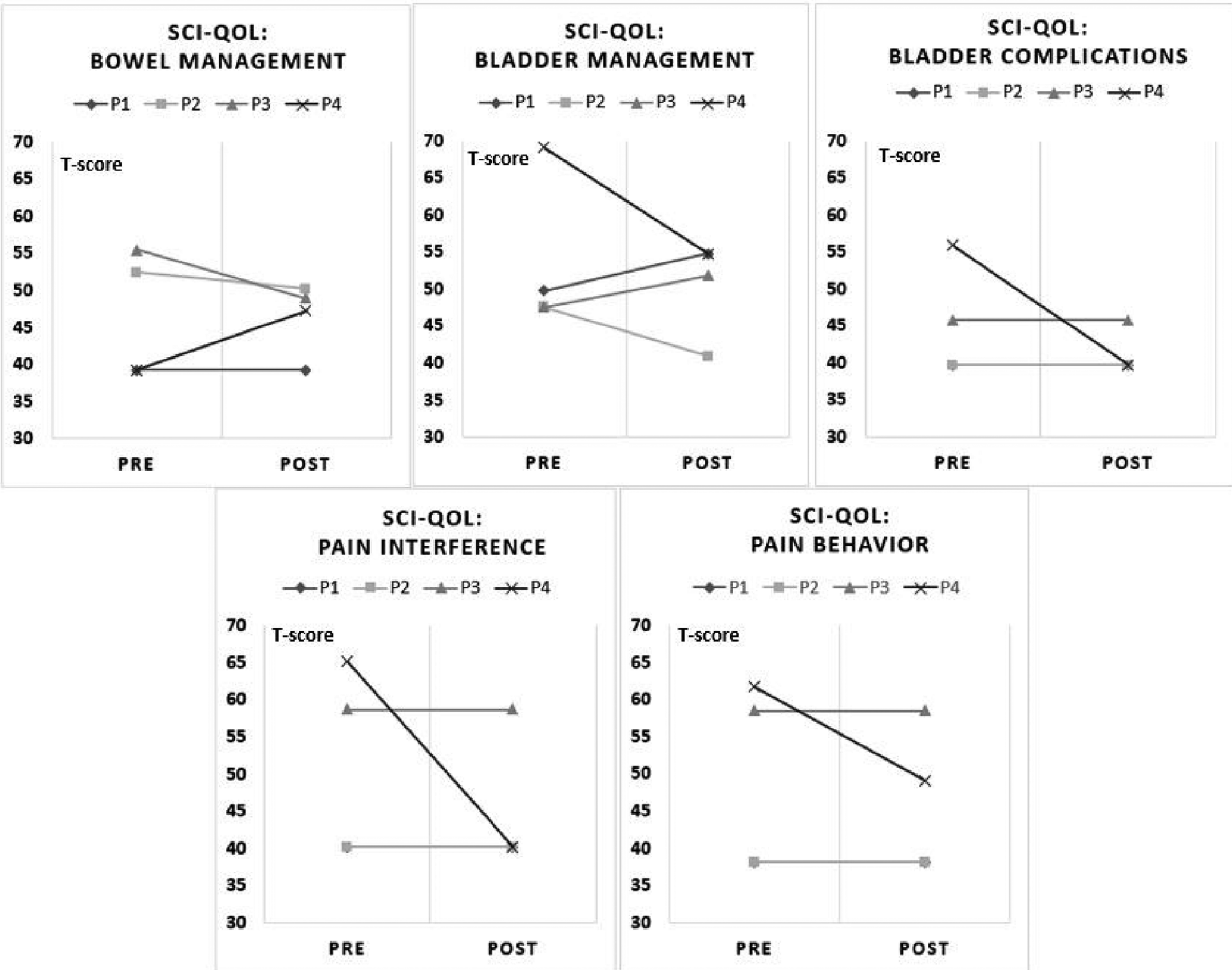

FIGURE 3
Charts of pre-post SCI-QOL by categories. Each panel depicts five components of the SCI-QOL physical-medical-health domain (18, 19). A reduction in scores from pre to post indicate an improvement.

A passive position change may not be as beneficial as physical activity. In the participants tested, all were unable to conduct an active position change from sit to stand. Our study focused on safety, tolerability, and the participant satisfaction with the device. A future controlled and appropriately powered study to determine the effect of regular passive standing would be indicated.

For the category, "Pressure Relief", participants rated the UPnRIDE as "very good". Especially P1, who had a skin issue which needed frequent pressure relief of an area. P1 reported a benefit from using the position changes of the UPnRIDE standing power wheelchair and the participant was very satisfied with the pressure relief. Since the UPnRIDE standing wheelchair provides various seated functions, participants were satisfied with the reclined position while resting and the stability of standing position.

In the current version of the UPnRIDE device limitations with transferring were reported because of the static knee hinges. Although participants were satisfied with the UPnRIDE overall, it was difficult for them to independently transfer in and out of the device. Participants reported being uncomfortable with the stability of the device while adjusting positions but felt secure once in the standing position.

Patient-reported outcomes for bowel, bladder and pain were variable. P2 (AIS D) had two bowel accidents during the middle sessions, then did not have any accidents for the remainder of the of study sessions, likely attributable to subsequently requiring the participant to empty their bowel and bladder on the days prior to their sessions. The act of standing did not appear to have any appreciable benefits for pain reduction, particularly in the case of P3. P3 had chronic pain with and without using UPnRIDE. P4 had improvements on most categories, except bowel management. P4 is a manual wheelchair user, so the participant reported being able to use his upper extremities more freely with a greater range using the UPnRIDE. However, the extra safety security systems (chest harness, knee brackets, and seat belt) posed difficulties with doffing the device when needing to managing bowel movements compared with using a manual wheelchair with one seatbelt. Because of the variability among the four participants for the patient-reported outcomes on bowel, bladder, and pain, more participants need to be tested to draw any conclusions.

TABLE 4 Participant-reported overall satisfaction with UPnRIDE standing wheelchair.

	P1	P2	P3	P4
Comfort	4	4	4	5
Feel of the ride	4	4	5	5
Support	5	4	5	5
Stability	5	4	5	5
Ease of transferring	3	3	4	5
Body position of adjustment	4	3	4	3
Stability of adjusting	3	3	4	3
Comfort of adjusting	3	3	4	4
Reclined position while resting	5	4	4	5
Stability of standing position	5	4	5	5
Comfort of standing position	4	4	5	5
Usefulness with daily life	4	4	5	5
Pressure relief	5	4	5	5
Things liked MOST	(1) Ability to operate outside while standing. (2) Pressure relief of sore while standing and continue daily activity.	(1) The ability to stand. (That would come in handy at work.)	(1) The ability to stand at eye level.	(1) The ability to stand. (2) Weight on legs and Pressure relief of butt.
Things liked LEAST	(1) Difficulty transferring. (2) Tight Upper straps.	(1) Battery power goes quickly (3–4 h with frequent changes of position), needs extra batteries.	Nothing reported	(1) Not liking the position change from seated to standing felt awkard and like they were leaning too far forward.

Rating scale: 1 = Very Poor, 2 = Poor, 3 = Moderate, 4 = Good, 5 = Very Good.

5 Limitations

A major limitation of the current case series is that the study was conducted with a small sample size with different levels and completeness of SCI. The training duration for each session varied and was primarily based on the availability and tolerability of the participants. Therefore, these findings are not generalizable. Knowledge from this data may serve as a basis for other clinical studies to establish standing protocols in other existing standing wheelchairs or ones yet to be developed.

The design of the device's leg rests presented limitations for participants when transferring in and out of the UPnRIDE wheelchair which required assistance and significant effort and time. Three more subjects were enrolled in the study at the time a research hold was placed due to the Covid-19 pandemic and were unable to complete the study.

6 Conclusions

This upright, standing wheelchair provided users a new level of mobility and freedom of upper extremities. Using the UPnRIDE also required less upper body function than current exoskeletons making it more practical for a wider range of people with SCI. The standing position supports stretching of the lower extremities. This is an important consideration because contractures restrict not only standing and walking, but dressing and other activities of daily living. Maintaining range of motion in the lower extremities would be needed for participation in further technological advancements that use upright positions.

The current case series in four participants suggests that use of this power wheelchair is feasible for upright overground mobility. Using an upright standing power wheelchair was demonstrated to be safe, feasible, and effective within one session of training. Most participants performed all functions of mobility skills and reported "comfortable/very comfortable" on the comfort scales. Appropriate HR and BP responses were demonstrated throughout the training sessions and the BP difference from seated to standing position decreased by the end of study. Some participants reported reductions in bladder complication, pain interference and pain behavior. Also, they were generally satisfied with the device, especially with support, stability, reclined position while resting, and stability of standing position. There may be greater benefits if participants are able to use the device for a longer period of time, such as during home use. Various upright wheelchairs, such as Permobil, Quickie, and Ki Mobility, offer distinct features and capabilities. Though not as mobile as exoskeletons or the UPnRIDE, they may still provide advantages to individuals with SCI who cannot use exoskeletons.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study was approved by the Institutional Review Board (IRB) of the James J. Peters VA Medical Center (JJPVAMC), Bronx, NY. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the participant/patient(s) for the publication of this case report.

Author contributions

EH: Writing – original draft, Writing – review & editing. AS: Writing – original draft, Writing – review & editing. ME: Writing – original draft, Writing – review & editing. SK: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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