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Exploiting Virtual Reality to Design Exercises for the Recovery of Stroke Patients at Home

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Abstract. Stroke affects approximately fifteen million people worldwide annually, with impaired hand function being one of its most common effects. Hemiparetic post-stroke patients suffer a mild loss of strength involving one side of their body: though not fully debilitating, it still impacts their everyday life activities. To prevent mobility deterioration, patients must perform well-focused and repetitive exercises during chronic rehabilitation. Virtual Reality (VR) emerges as an interesting tool in this framework, offering the possibility of training and measuring the patient's performances in ecologically valid, engaging, and challenging environments. In recent years, there has been an increasing diffusion of accessible head-mounted displays that enhance the sense of realism and immersion in a virtual scene. To explore the feasibility and efficacy of VR immersion and game mechanics in rehabilitation programs, a VR system that allows users to rehabilitate their motor skills in a home-based environment has been designed and tested considering standard measures related to usability, immersion, workload, and simulator sickness, and with the involvement of rehabilitation experts. The results demonstrate how users and experts have received the application positively, highlighting the potential of VR applications for the future development of home-based rehabilitation programs.

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1 INTRODUCTION

A stroke, or brain attack, is a medical condition causing long-term disorders, including cognitive impairments and motor disabilities. The most common consequence affecting nearly 70% of stroke survivors is hemiparesis, a mild loss of strength on the affected side and limb, resulting in the loss of one's independence as regards daily living activities' performance. For lifestyle recovery, the rehabilitation phase is crucial: tests conducted within rehabilitation programs show that patients' functions are retrieved if they perform repeated exercises identified with a specific goal [16]. However, traditional therapies are often found to be monotonous and boring due to their intrinsic repetitiveness [7]. While the initial recovery phase mainly occurs in hospitals, patients are subsequently required to carry out home-based programs.

In recent years, there has been a growing focus on extending the employment of Virtual Reality (VR) technology in rehabilitation. Its application is proven to come with potential advantages for many aspects of rehabilitation research and treatment. More specifically, the possibility of training one's motor abilities in ecologically valid environments that are both challenging and safe allows individualized treatments tailored to the patient's specific needs and readjusted based on their progress [17]. Finally, thanks to the recent developments in the quality and accessibility of head-mounted displays, users develop a sense of 'being there', perceiving virtual characters and objects as actual social agents [10].

Studies comparing the differences between stroke individuals treated with rehabilitation gloves coupled with SVR (Semi-immersive Virtual Reality) applications and treated with conventional therapy have been considered over a database of more than 1400 studies. Results have shown that the combined use of gloves and exoskeletal devices with SVR systems for the rehabilitation of post-stroke patients, especially during the acute and sub-acute phases, provides significant improvements over conventional rehabilitation treatments in the functionality recovery of stroke patients [6]. Also, the number of commercial solutions currently available on the market and used in clinical settings that adopt SVR in post-stroke rehabilitation is slightly increasing. Two examples are the Neofect Smart Glove and the Gloreha Glove device. The first uses, in combination with a sensorized glove, desktop-based VR gamified exercises to challenge and motivate the patient. The serious games include activities of daily living, repetitive task-oriented training, and leisure games [15]. On the other hand, Gloreha is a robotic device capable of performing passive and active-assisted movements on the patient's hand. At the same time, the patient is given the possibility to watch a 3D screen simulation of his/her hand in motion to stimulate neuroplasticity and force the patient to focus on the hand movement [3].

We designed a VR application effectively targeting patients' motor rehabilitation and engagement-related issues in a home-based environment. The targeted end-users are hemiparetic post-stroke patients. The proposed gamified versions of traditional therapeutic exercises are centered on their upper limb movement and the most common hand grasp types. The possibility for therapists to keep track of patients' results and progress has also been tackled.

2 DESIGN METHODOLOGY

A deep analysis of the design patterns crucial for rehabilitation purposes is required to design VR applications capable of effectively targeting cognitive and motor deficits. As regards the proposed VR system, three main goals have been identified:

- **Upper-limb motor abilities preservation and improvement:** the proposed rehabilitation system must be capable of preserving, if not improving, patients' physical capabilities in a systematic manner.
- **Patients' engagement and motivation:** promoting user adherence to rehabilitative training, increasing their potential successful outcomes.
- **Tracking of patients' performances:** in-game data is a crucial measure to predict user performances when facing real-life challenges.

The main design patterns required to fulfill such goals have been derived from the scientific literature and integrated with assessments carried out in collaboration with therapists and rehabilitation experts of Villa Beretta Rehabilitation Center. The aroused main requirements are reported as follows:

- **Gaming features:** as one of the main challenges faced in home-based rehabilitation is the lack of patients' motivation, the integration of gaming features can enhance it [11], especially cognitive challenges that are easy to learn yet hard to master [14].
- **Error-free learning:** positively handling failure in rehabilitation exercises makes patients more likely to remain engaged without feeling penalized by their motor impairments [5].
- **Performance feedback:** these features not only respond to the ongoing status of the patient's performance but can be exploited as motivators, leading to increased enjoyment and a consequent greater desire to complete particular tasks [19].
- **Difficulty progression:** exergames should be initially paced to encourage the patient's engagement [1], with gradual difficulty progression based on their performance.
- **Ecological validity:** it strongly relies on the capability of resembling key real-life challenges rather than the graphic realism level [18].

Four categories were finally identified to properly evaluate the defined primary goals: well-being, workload, general user experience, and engagement.

3 VIRTUAL ENVIRONMENTS DESIGN

The VR scenarios have been designed using the Unity engine (2021.3.9f1) and the Meta Quest 2 device SDKs. Its feature exploited for the VR application design is hand tracking: it detects the user's hand position and orientation and the fingers' configuration through computer vision algorithms.

In Fig. 1, the general VR application's structure is displayed. At the beginning of each session, users are provided with an initial demo scene to practice and familiarize themselves with the main in-game interactions before the actual training session. In this scene, the principal game-objects and their associated interactions with which the user can deal in the different exercises are presented. Two main exercise sections (i.e., Hand Grab and Hand Movement Exercises) and the respective interactive menus are subsequently provided. While the former allows patients to interact with game objects by performing simple clenched fist grasps, wrist pronation, and supination movements, the latter is devoted to training the principal hand prehension types. Considering the human grasps taxonomy reported in Yang et al. [20], the ones introduced in the designed rehabilitation exercises are cylindrical and spherical power grasps, pinch, and tripod precision grasps.

Rehabilitation exercises have been designed to be used without walking to avoid potential unpleasant consequences due to VR cybersickness. The maximum exercise duration set accordingly with the medical staff is three minutes to prevent patients' boredom while still triggering their mobility progress. As regards hand grab exercises, hand pose detection has been enabled and calibrated within each scene. The latest Meta SDKs provide components and configurators detecting when tracked hands match shapes (finger features) and transform (wrist orientations) set by the developer. Hand poses have been recorded using a replica of the actual tracked hands' for each game object (i.e., for each hand grab type). A specific acceptability range has been set: a range of correct poses is considered valid for the in-game user's interactions.

The scoring mechanism is unified among all the exercises and simplified in coins. Positive visual and auditory feedback has been associated with correctly performed targeted actions to help patients keep track of their ongoing status and motivate them during training. Finally, a paced learning strategy has been adopted: simple initial levels allow patients to familiarize themselves and engage with the Virtual Environment without feeling excessively penalized by their motor impairments.

Both VR exercises and the demo scene are accessible from an initial hand-interactive menu, displayed in Fig. 2. The exercise selection and the menu navigation are performed using the user's pinch hand gesture, while the demo scene selection is performed through a poke-interactive secondary menu: pressing the dedicated button with one's index finger, a switch between the two exercises' sections and the demo scene takes place. To

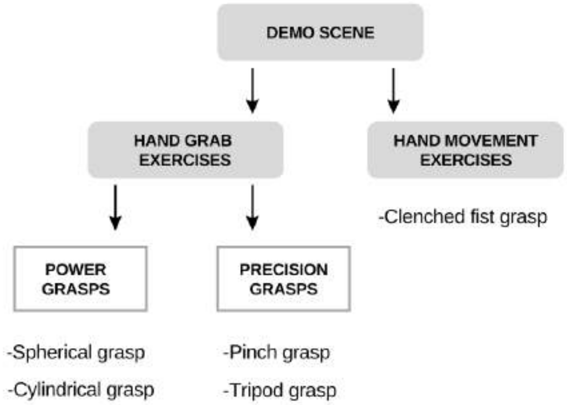


Figure 1: VR exercises design structure

foster patients' motor and cognitive improvements through their procedural memory stimulation, the exercises are characterized by rule-based automatic procedures.

Considering the Hand Movement exercises, in the first, users are required to rotate a handle to collect coins subsequently appearing at different angular positions. The increasing difficulty is reflected in a more comprehensive angular range that must be tracked and reached. In the second Movement exercise, users must horizontally translate the mug to collect coins falling from the virtual roof in different positions. Patients are therefore required to visually track them as they descend, subsequently grabbing and placing the mug in the necessary location. Higher difficulty levels have been paced relying on the coins' falling speed, keeping the primary mechanism unchanged. An example of an exercise session is presented in Fig. 3. The mug is associated with the clenched fist position. This particular grip type has been introduced to let patients train the wrist pronation and supination movements in dedicated exercises without being forced to perform, at the same time, a specific hand grab. Many patients, especially during their first recovery steps, are still not able to successfully reach intermediate fingers configuration and tend to directly close the whole hand in a fist. Thanks to the introduction of this interaction type, it is possible to gradually guide patients towards configurations in which their wrist pronation and supination movements need to be combined with specific grips.

Hand Grab exercises include both power and precision prehension exercises (Fig. 4). In the spherical and cylindrical power grasps the user interacts with two simple geometries, a sphere, and a cylinder. The standard game logic of this set of exercises is based on pick-and-place actions, particularly crucial for hemiparetic patients as they are forced to iteratively open and close their limbs until reaching the correct grasp configuration. The game logic is dictated by the common characteristic of both object and grid squares, i.e., their color, which is considered a "cueing stimulus" given before the expected patient response to guide it successfully. Two additional Grab exercises deal with precision pinch and tripod grasps. In the first, keys of different colors appear in front of the user, who combines and inserts them in the lock of the corresponding color, performing a pinch grab. In the second, the user interacts with a spray bottle: a pot plant must be watered by iteratively performing a tripod grasp. Once the correct fingers' configuration is reached, a vaporized water jet animation is triggered, and the score is increased by one point. For each exercise, a range of three different difficulty levels is provided.

The user's in-game score relies on the correctly performed actions within every scene and is displayed in

Figure 2: The initial hand-interactive menu of the application

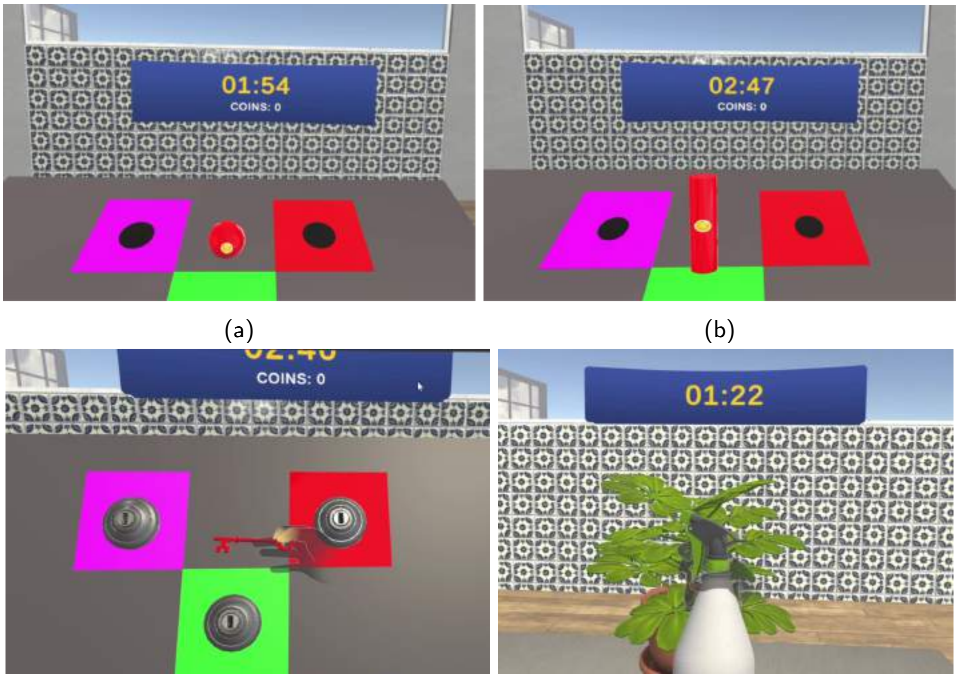
(a)

(b)

Figure 3: An example of hand movement exercise. A user while performing a Hand Movement exercise (a) and their point of view (b).

the background during the exercise execution. Once finished, it is stored in a .txt file automatically generated within the project folder. This way, the medical staff can monitor patients' performance over time. On top of that, at the beginning of each session, it is possible to set the number of users participating, potentially making comparisons between different recovery paths.

A more detailed grasping analysis has been integrated to monitor finer movements' recovery precisely. Meta Quest 2 cameras are used for hand tracking as the exercise unfolds: positional and rotational data are recorded within Unity software with a frequency of $10Hz$. Coordinate systems are associated with each of the fingers' joints: during their motion, the angle between the axis belonging to adjacent bones gives the angle between them. Such data are then imported into MATLAB to evaluate the patient's grasping performance. For this purpose, the SynGrasp Toolbox has been employed: it allows the description of their kinematic structure in terms of links, joints, and reference frames.



(a) (b)

(c) (d)

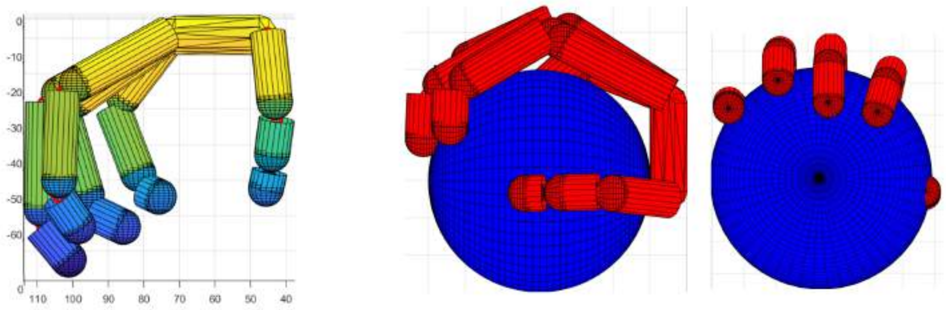
Figure 4: Grab exercises for spherical (a), cylindrical (b), precision (c), and tripod (d) grasps.

The Denavit-Hartenberg (DH) parameters notation is employed for the hand structure definition, and a table containing each finger's DH parameters is provided within the toolbox. For this project, the 20 DoF anthropomorphic hand model has been employed. The joint variables $q = [q1q2...qn]^T$, corresponding to the user's fingers' relative rotations, have been imported from the user's hand-tracking data in Unity3D. The hand's forward kinematics has been calculated by using as inputs the anthropomorphic hand model defined within the SynGrasp Toolbox and the imported joint variables q. It is finally possible to 3D plot the hand-grasping configurations assumed by the user during the exercise execution. A configuration is reported in Fig. 5.

4 PILOT STUDY

Pilot tests have been performed to evaluate the designed VR application's potential benefits and limitations. An initial study has been conducted on two main patient samples, namely 'hemiparetic' and 'suffering from cognitive impairments', to assess the general user experience using the System Usability Scale (SUS) [4] administration. This study was carried out at the Politecnico di Milano, in collaboration with the Villa Beretta Rehabilitation Center and the Aspoc Lab Onlus association, on 15 patients.

Test results have been integrated with rehabilitation experts' assessments. The obtained SUS scoring has been promising, and general positive responses were reported: the experience was perceived as challenging and engaging by patients. Rehabilitation experts identified as the main strength the total patient's independence during their therapy performance, thanks to the hand tracking integration. However, a limitation in set-up was identified for patients requiring to perform motor therapy in an upright position. Finally, an interest emerged in data collection regarding the exercises' execution precision: the hand-grasping analysis in MATLAB software has been integrated at this stage. Following the initial usability study, more extended user testing has been



(a) (b)

Figure 5: The hand model from the Matlab SynGrasp Toolbox (a) and a configuration assumed by the user' hand during a grasp exercise (b).

performed in light of the proper integrations that emerged during the previous stage.

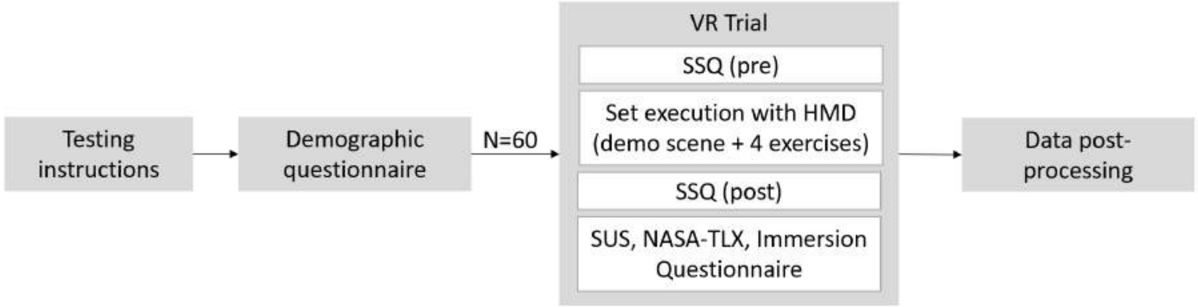
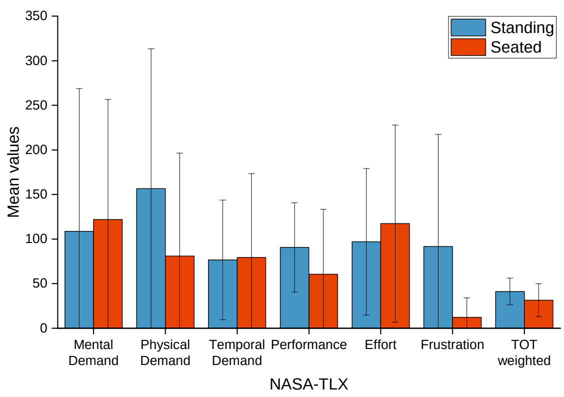


Figure 6: Procedure of the experimental study. 60 participants completed the VR trial in balanced randomized order. They performed the proposed set and answered questionnaires afterward. The SSQ was completed before and after VR exposure.

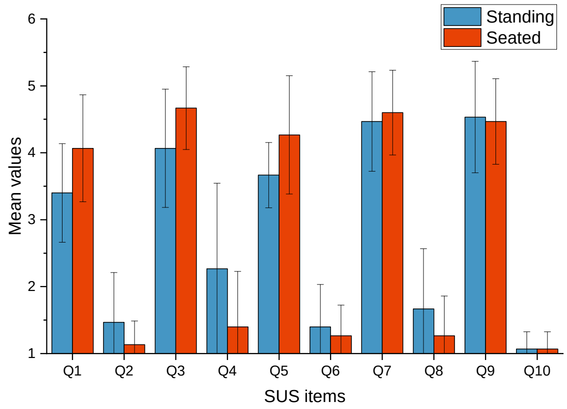
Established psychometric instruments have been used to gather data related to users' workload perception (using the NASA-TLX questionnaire [9, 8]), immersion [12] and potential VR sickness (using [13]). The testing was undertaken at Politecnico di Milano: 60 participants (25 females and 35 males) aged between 19 and 48 were recruited. The hand pose detection feature was deactivated before the testing phase to let participants freely manipulate the proposed game objects. Fingers' positional and rotational data were recorded and stored during their testing. The central scene's colors were modified and blurred to simulate potential cognitive deficits in healthy participants. Fig. 6 shows the procedure of the experimental study.

Upon arrival, each participant was asked to fill in a demographic questionnaire and the Simulator Sickness Questionnaire (SSQ). Each participant performed four out of the seven exercises available in a counterbalanced order using a Latin square design. The overall participant sample was divided into two sub-groups of thirty each: one group performed the set of exercises while seated, and the other while standing.

Each session lasted approximately 20 minutes. Once the trial was completed, participants were asked to remove the headset and complete the SSQ again, followed by the NASA-TLX, the SUS, and the Immersion



(a) NASA-TLX weighted results. Scores are referred to the Standing and Seated configurations.



(b) Mean values for each item of the System Usability Scale (SUS) in the Standing and Seated configurations.

Questionnaire.

Considering NASA-TLX indexes (Fig. 7a), moderate increases are to be found for what concerns the participants' perceived mental demand and effort in the seated configuration, while the standing one has generally challenged participants in terms of physical demand and frustration, making their overall perceived workload increase.

Once again, the SUS scores were quite promising (mainly in the excellent band according to Bangor et al. [2]). In fact, the final SUS scoring is a single number constituting a composite measure of the overall analyzed system's usability. Based on the literature, the average SUS score is 68 and therefore corresponds to the 50th percentile. Fig. 7b shows the result of the SUS questionnaire. In the case of the standing testing configuration around 63.3% of participants expressed an overall score belonging to the Excellent band, while the remaining 36.7% belonged to the Good band. In the case of the seated configuration around 90% of participants expressed an overall score of Excellent rating and the remaining 10% of Good rating.

Similarly, the perceived participants' immersion marked a general sense of time-track losing and in-game presence. Most of them stated that they forgot their everyday concerns during the trial and strongly focused on the proposed exercises. In Fig. 8 results are presented for both configurations in terms of mean and standard deviation.

An increase in the SSQ symptoms has been generally detected after the VR trial, especially for the Disorientation index where most participants reported slight symptoms, with a few cases of moderate post-trial symptoms. In Fig. 9 the main symptoms' scores are displayed. The reported data are referred to both pre-test and post-test participants' conditions in both standing and seated configurations. SSQ questionnaire's answers were translated into a number, from 0 = None to 3 = Severe, and scores have been converted following the procedure described in [13].

5 CONCLUSIONS

This work focused on designing and piloting a VR-based rehabilitation system to recover upper-limb functions for hemiparetic post-stroke patients.

The main design patterns that effectively target cognitive and motor impairments due to brain attacks have been tackled. The implemented VR scenes have been designed using the Unity3D engine coupled with Meta Quest 2 headset, exploiting its hand-tracking capability. Two main exercise sections have been designed, targeting both hand movements and the most common prehension types. Data post-processing has been

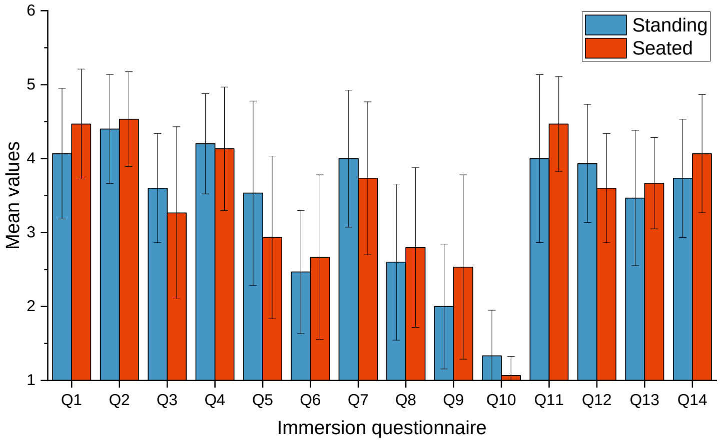


Figure 8: Mean values for the Standing and Seated configurations related to each item of the Immersion Questionnaire [12].

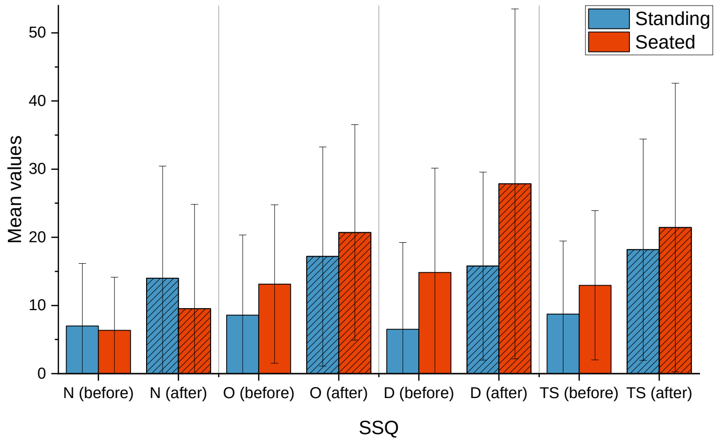


Figure 9: Simulator Sickness Questionnaire (SSQ) scores. Scores are referred to before and after VR trial performance and to the Standing and Seated configurations. The different symptom groups along the x-axis are: Nausea (N), Oculomotor (O), Disorientation (D), and the Total Sickness (TS).

integrated regarding the general in-game performances and a more in-depth analysis of users' finer manipulation skills. A final pilot test has been conducted: established psychometric indexes have been employed to evaluate the system's usability and participants' immersion, perceived workload, and simulator sickness.

Further studies will include more in-depth research regarding the minimization of users' perceived discomfort, characterized by different therapy time lengths. In this way, the optimal duration, resulting from a trade-off between the required upper-limb motor recovery level and the perceived cyber-sickness, can be determined. Finally, future works, at a later stage in the design process, would involve patient testing: the VR system's therapeutic effects could be investigated in controlled experiments involving a large sample of post-stroke hemiparetic patients. This work would probably demand a significant effort, but the potential final results may be of great scientific value. Patients would be provided with a much more engaging therapeutic experience in a home-based environment, demonstrating how VR technology could tangibly increase the quality of life, offering affordable, effective, and accessible alternatives in the clinical rehabilitation field.

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