Title:
A design methodology to exploit Virtual Reality for the recovery of stroke patients at home

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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 [10]. However, traditional therapies are often found to be monotonous and boring due to their intrinsic repetitiveness [3]. 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, allowing for individualized treatments tailored to the patient's specific needs and readjusted based on their progress [11]. Finally, thanks to the recent developments in terms of quality and accessibility of head-mounted displays, users develop a sense of 'being there', perceiving virtual characters and objects as actual social agents [6].

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 centred 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.

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 [7], especially cognitive challenges that are easy to learn yet hard to master [9].
- **Error-free learning:** positively handling failure in rehabilitation exercises makes patients more likely to remain engaged without feeling penalized by their motor impairments [2].
- **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 [13].
- **Difficulty progression:** exergames should be initially paced to encourage the patient's engagement, 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 [12].

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

Virtual Environments Design:

The VR scenarios have been designed using the Unity3D engine (2021.3.9f1) and the SDKs of the Meta Quest 2 device. 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.

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. Two main exercise sections, i.e. Hand Grab and Hand Movement Exercises, together with 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. [14], the ones introduced in the designed rehabilitation exercises are cylindrical and spherical power grasps, pinch, and tripod precision grasps.

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.

(a) A user performing a Hand Movement exercise. (b) Users' point of view during a Hand movement exercise.

Fig. 1: An example of Hand movement exercise.

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 exercise session is presented in Fig. 1.

Regarding Hand Grab exercises, three include both spherical and cylindrical power prehension types so that 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 colour, which is considered a "cueing stimulus" given before the expected patient response to successfully guide it. Two additional Grab exercises deal with precision pinch and tripod grasps. In the first, keys of different colours appear in front of the user, who combines and inserts them in the lock of the corresponding colour, 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 vaporised 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 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 precisely monitor finer movements' recovery. Meta Quest 2 cameras are used for hand tracking as the exercise unfolds: positional and rotational data are recorded within Unity3D 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: developed for the evaluation of human hand models, it allows to describe their kinematic structure in terms of links, joints and reference frames.

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) [1] administration. This study was carried out in Politecnico di Milano, in collaboration with the Aspoc Lab Onlus association and Villa Beretta Rehabilitation Center, 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. Following the initial usability study, more extended user testing has been performed in light of the proper integrations that emerged during the previous stage.

Established psychometric instruments have been used to gather data related to users' workload perception (using the NASA-TLX questionnaire [5, 4]), immersion and potential VR sickness (using [8]). The testing was undertaken at Politecnico di Milano: 60 participants (25 females and 35 males) aged between 19 and 48 were recruited. Fingers' positional and rotational data were recorded and stored during their testing. Upon arrival, each participant was asked to fill in a demographic questionnaire and the Simulator Sickness Questionnaire (SSQ). Each participant performed 4 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 30 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 SUS, the Immersion Questionnaire and the NASA-TLX.

Once again, the SUS scores were quite promising (mainly in the excellent band), as well as the perceived participants' immersion, which 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. An increase in the SSQ symptoms has been generally detected after the VR trial, especially for Nausea and Oculomotor categories concerning the standing condition where most participants reported slight symptoms, with a few cases of moderate post-trial symptoms.

Similar results where obtained for mental and temporal demand, performance, and frustration indexes of the NASA-TLX, with only a slight increase registered in the standing configuration, while moderate increases are to be found for what concerns the participants' perceived physical demand and effort in the seated one.

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

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