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Design and development of VR-based exergames for functional hand rehabilitation after stroke

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1. Introduction

Stroke is one of the world's leading causes of disability, particularly when it comes to the motor skills needed to carry out daily tasks and professional commitments. A large proportion of stroke victims suffer from impaired motor function in their upper limbs. Even after recovery, many stroke survivors encounter difficulties in their daily activities due to persistent problems with upper limb functionality, necessitating medical intervention through rehabilitation. The field of functional rehabilitation in rehabilitation centers is in need of significant enhancements in terms of rehabilitation tools. Conventional clinical protocols for functional rehabilitation often fall short due to issues such as boredom, affecting patients' motivation and subsequently hindering the recovery of their motor functions. In response to these challenges, innovative therapies like virtual rehabilitation have emerged as promising alternatives. Virtual rehabilitation involves the use of virtual reality (VR) therapy, utilizing software systems that simulate real-world tasks to enhance rehabilitation for stroke patients (Figure 1).

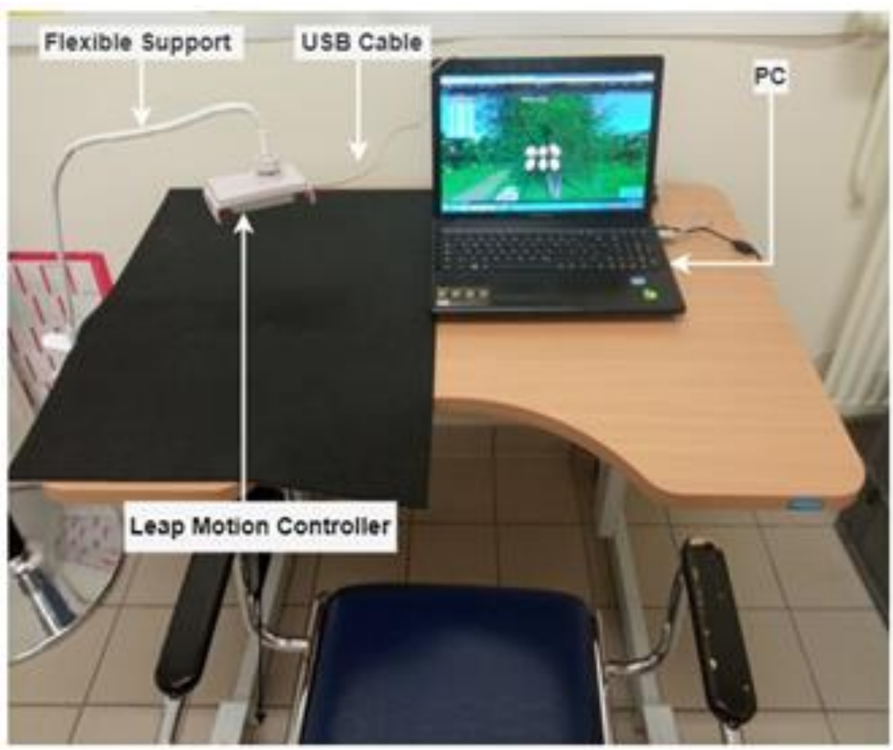

Figure 1. System hardware components [5].

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One notable aspect of virtual rehabilitation is the incorporation of serious games, a form of gamification, into motor rehabilitation after stroke. Exergames, which inject an element of enjoyment into rehabilitation exercises. Gamification transforms rehabilitation into an enjoyable experience, requiring participants to engage in physical activities that involve specific body movements. The primary goal of stroke rehabilitation is to promote cerebral plasticity and functional compensations, requiring a personalized approach tailored to individual patient needs based on factors such as stroke severity, age, and pre-stroke occupation , and VR technology offers customizable and engaging environments for rehabilitation . The ideal VR platform for functional rehabilitation, should not only motivate patients but also offer personalization and adaptability in the form of progressively challenging exercises [1]. In recent years, artificial intelligence (AI) has played a pivotal role in advancing human welfare, particularly in the realm of rehabilitation methods. In this context, our paper presents a functional rehabilitation system based on VR and integrating serious games, aimed at enhancing patients' motivation, commitment and therapeutic adherence.

The system has been designed and developed, taking into account various criteria associated with the clinical specifications of the medical context concerned. The design process involved close collaboration with therapists and patients, and validation was carried out with post-stroke patients. Simulated clinical exercises were chosen to ensure that the system was perfectly aligned with the clinical specifications. These exercises were tested, evaluated and validated beforehand, demonstrating their therapeutic effectiveness. Particular attention was paid to the scenario, customization and adaptive difficulty during the design and development phases. Subjective evaluation of the system was carried out using standardized questionnaires.

2. Method

The activity scenario

Gamified exercises help the user train complex skills required for everyday activities that involve the same movements. Thus, an activity is linked to the values and culture of the person and the occupational therapist must ensure that the proposed activity is meaningful for the person who is sufficiently committed to relearn how to practice the activity.
Consequently, as part of the VR-based serious games we designed, an environment representing a virtual farm was chosen, which constitutes a user-friendly environment. Great care was taken in designing this environment.
The environment consists of a set of fruit trees. In which the user is encouraged to perform a fruit harvesting activity, in order to carry out the predefined movements.

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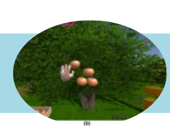
Hardware and software system

The hardware system used in this work consists of a computer, connected to a hand motion sensor which is Leap Motion controller (LMC). The LMC is a non-contact motion capture device that allows the user to interact in a virtual environment. This sensor has two infrared cameras in a stereo vision configuration [2]. It provides data on the position of the user's finger phalanges [3]. It tracks in real time the 3D positions of each finger bone in a field of view of 135 to 120 frames per second [2] . The LMC SDK uses an internal model of the human hand to provide predictive tracking, even when parts of the hand are not visible. This model always provides the positions of the five fingers, but tracking is optimal when the outline of the hand and all its fingers are clearly visible. The software uses the visible parts of the hand, its internal model, and past observations to calculate the most likely positions of the parts that are not currently visible. Thus, given that a stroke patient with moderate to severe symptoms may only be able to move their arm to a small extent [4]. Therefore, to allow patients with low mobility/strength to be able to place their paretic limb on the table so that they do not have to fight against gravity, we placed the Leap Motion© sensor upside down over the patient's arm. Thus, the Leap Motion© sensor was placed above the table on a universal flexible support for smartphone. The complete hardware architecture of the system is presented in Fig. 1. The exergames was developed using Unity 3D and the scripts were realized by the C# programming language. Thus, to obtain the 3D vectors of the palm positions and finger joints, the LMC Software Development Kit (SDK) was used. To implement the exergame adaptation system, we used the Python programming language.

Exergames

The system is designed primarily for functional rehabilitation of the hand. Two activities have been selected, which can be performed in a seated position, with the aim of recovering motor skills in the hand. One consists of training a coarse hand movement called "palmar grip", and the other a fine hand movement called "bidigital grip". Indeed, we agreed to simulate two clinical exercises, in an attractive virtual environment with intuitively simple virtual activity scenarios.

1) Palmar grip exergame: Coarse dexterity, essential for handling large objects, is crucial in a variety of everyday and professional activities. To improve this motor skill, we created an Exergame simulating two clinically proven exercises focused on strengthening palmar prehension. The first exercise involves manipulating a ball to develop finger flexion and hand-finger coordination. The second, uses modelling clay to strengthen the muscles associated with finger flexion and improve movement control.
2) Bidigital grip exergame: Fine dexterity is crucial for handling small objects in everyday and professional life. To improve this motor skill, we have created a game simulating two clinically proven exercises to train bidigital grasping. These exercises consist of a terminal opposition pinch, for gripping very fine objects, and a sub-terminal opposition pinch, ideal for holding objects such as a pencil or sheet of paper.



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3) Virtual environment: In the VR games, the patient has a semi-immersive experience on a virtual farm with fruit trees. The palmar grip exergame involves medium-sized fruits, such as oranges and apples, corresponding to the dimensions of a human hand and resembling the balls used in clinical exercises, while the bidigit grip exergame includes relatively small-sized fruits, such as cherries, in the virtual environment. Here, patients are asked to perform finger flexion movements resembling those used in simulated clinical exercises to pick the virtual fruit.

Tasks

In order to increase the realism of this activity, we added to the set of movements evoked by the simulated exercises a set of sensory-motor tasks necessary for the natural performance of the activity. In both exergames, to succeed in the game, the patient must perform the following tasks:

Figure 2. The scenes representing the virtual environments where the games occurs .

- A pointing task: In this task, participants perform the palmar grasping exercise by moving their hand towards the fruit and using their palm to indicate it. In the bidigital grasping exercise, the index finger is used to point at the fruit, enabling the patient to pick it up more easily afterwards.
- A grasping task: In the palmar grip exercise, patients have to flex their fingers to bring them closer to the palm. In the bidigital grip exercise, the task is to bring the thumb and index finger as close together as possible, enabling patients to effectively grasp the fruit they have pointed to.
- A deposit task: In the palmar grip exercise, participants extend their fingers away from the palm to open the hand. In the bidigital grip exercise, they separate the thumb and forefinger to free the fruit placed between them, set it down, then place the freed fruit in a basket.

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User representation

As mentioned earlier, our system is particularly interested in the functional rehabilitation of the hand. The hand is therefore the limb that will be in direct interaction with the entities of the virtual environment. As patients' hands are often deficient and retracted, we have chosen to display a virtual hand instead of the patient's real hand (Figure 3). This is supposed to give a more positive perception to the patients. The movements of the virtual hand are synchronized with those of the real hand.

(a) (b)

Figure 3. The virtual hand used in the exergame. (a) The hand's avatar . (b) Representation of the hand's avatar in the virtual environment [5].

Measurement of patient motion

The games on offer incorporate feedback from therapists to determine the amplitude of hand movements. The palmar grip exercise is characterized by the ability to open and close the hand, while the bidigital grip exercise involves moving the thumb away from the index finger. Range of motion is defined as the ability of the hand to open and close. This measure is determined by the distance between the fingertips (excluding the thumb) and the palm in the first exercise [5], and by the distance between the tip of the thumb and the index finger in the second exercise.

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Exergames difficulty

To enable actions in the games and determine their level of difficulty, we have established specific thresholds for the patient's finger movements. These thresholds serve as benchmarks and enable us to assess the patient's ability to perform specific tasks [5]. The patient's ability to perform these tasks successfully becomes the main criterion for defining the complexity of a game. By adjusting the difficulty of the game according to the patient's performance, we aim to provide a personalized and stimulating rehabilitation experience that matches the patient's skill level and promotes continuous improvement.

Exergames personalization

Game calibration is crucial to tailoring the difficulty level to the patient's current abilities. Before starting the game, the patient performs the specific finger movements required to complete the game tasks. These movements include actions such as opening and closing the hand in the palmar grip exercise, and separating and bringing together the thumb and index finger in the bidigital grip exercise. This initial phase encourages the patient to perform the fundamental movements essential for play.
To reinforce autonomy in the game, the system offers on-screen video tutorials illustrating the required movements. The aim of these tutorials is to provide visual and practical guidance, making it easier for the patient to understand and perform the required movements precisely [6].
The system assesses the patient's motor skills by measuring the amplitude of finger movements, in particular the maximum and minimum amplitudes achieved. Based on these measurements, the system establishes personalized thresholds corresponding to the patient's abilities. These thresholds are used as a reference to determine the appropriate level of difficulty for the game, ensuring that it is adapted to the patient's individual abilities.

Adaptive difficulty

In upper limb motor rehabilitation, preventing patient fatigue and maintaining motivation is crucial [7]. To achieve this, a dynamic approach is implemented that adjusts the difficulty level of the exergames based on the patient's motor skills. The system analyzes previous performances and utilizes unsupervised machine learning (clustering) to categorize patients into low, medium, and high-performance clusters. The K-means algorithm is employed, and the patient's performance is assigned to the most relevant cluster. By monitoring parameters such as attempts to grasp an object, the system detects the risk of fatigue and updates the game's difficulty accordingly. This personalized approach aims to strike a balance, ensuring the game is challenging enough to promote intensity but not too difficult to discourage engagement. The update involves adjusting thresholds with the average values of the cluster representing the patient's current motor abilities. Figure 4 shows a diagram of the dynamic difficulty adaptation approach.

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3. Results

Preliminary experimental tests

In order to evaluate and validate our system, we conducted a subjective evaluation of the acceptability and usability of the system by patients, using questionnaires to assess patient satisfaction with our system. In this context, we chose the standardized System Usability Scale (SUS) questionnaire [8] to assess the usability level of our system, and the Intrinsic Motivation Inventory (IMI) [9] to assess the subjective experience of the participants who used the system.

1) Experimental setup: Each participant was asked to sit on a chair facing a table with a matte infra-absorbent surface on it, and for visual feedback, a standard laptop screen was used (see Figure 5). The Leap Motion© sensor was placed above the table on a universal flexible support for smartphone, its rotation along the vertical axis will have been 0, and its position on the table is defined relative to the paretic limb, and it was placed at a height of 23 cm above the table. The sensor was calibrated (before the experiments) according to the method recommended by Leap Motion© until it reached at least the recommended score of 90. In order to ensure a better reading quality during the experiments, some precautions were taken, such as reducing interference from outside light, closing the windows so as not to be influenced by sunlight.

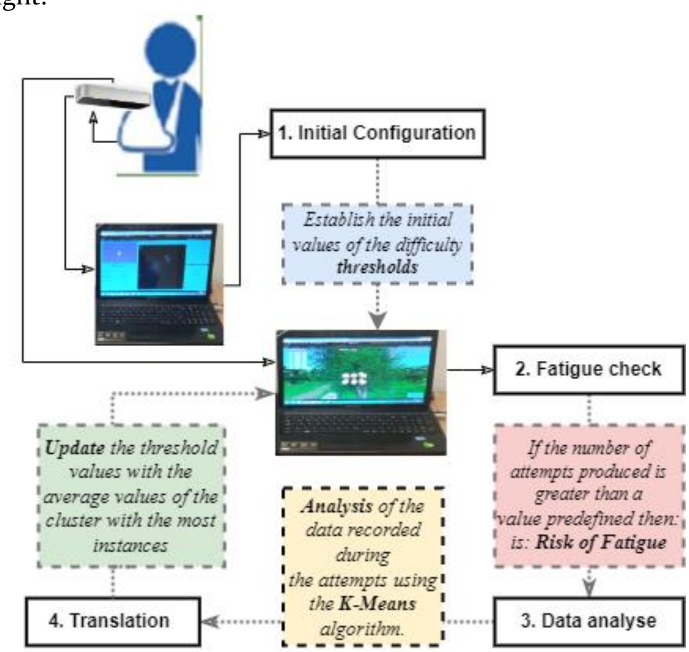

Figure 4. Dynamic difficulty adaptation diagram [5].

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2) Participants: A total of 11 participants were recruited (9 male, 2 female). These patients were not the same as those involved in the design process. All were stroke patients and with unilateral affection. The age of the patients ranged from 43 to 81 years, with a mean age of 66.2 (±10.31) years.

Results of the standardized SUS questionnaire

The results we obtained are shown in (Table I). The total is calculated according to the method given by the SUS questionnaire and goes from 0 to 100. The higher the score, the more usable the device. Figure 6 shows the SUS score of each participant.

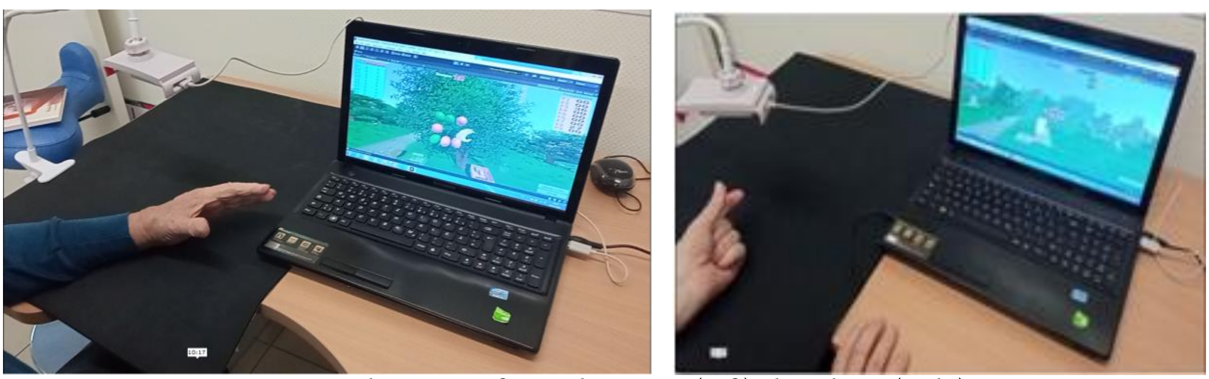

Figure 5. Patients in the process of using the system. (Left) Clinical test, (Right) Game test

Variable	Min	Max	Mean	Ecart-Type
Q1	1	4	3.09	0.83
Q2	1	4	2.9	1.13
Q3	1	4	3	0.89
Q4	1	4	2.09	1.37
Q5	3	4	3.63	0.5
Q6	2	4	3.45	1.68
Q7	1	4	3	1.09
Q8	1	4	2.9	1.51
Q9	1	4	2.81	1.25
Q10	1	4	1.81	1.16
Totale	55	100	71.81	11.24

TABLE I: Results SUS of Patients (n=11) [5].

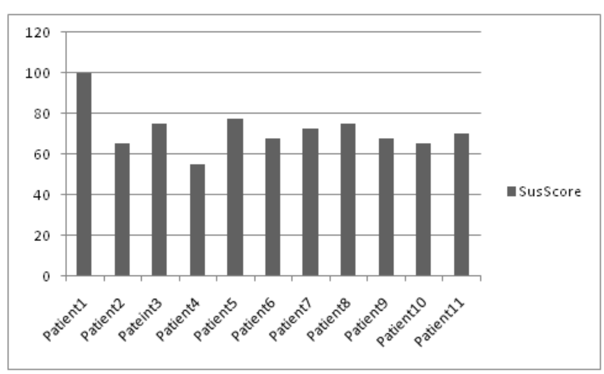

Figure 6. SUS Score [5].

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Results of the Intrinsic Motivation Inventory (IMI)

The Intrinsic Motivation Inventory (IMI) assesses participants' subjective experience with a target activity [9]. This 7-item Likert scale instrument was administered to assess participants' interest/pleasure; perceived competence; effort/ importance; and value/utility. Thus, we have calculated scores for each item: (Table II) shows the average IMI scores per participant shown in Figure 7.

IMI Item	Mean	Ecart-Type
Interest/Enjoyment	6.2	0.9
Perceived competence	5.21	1.01
Effort/Importance	6.09	0.9
Value/Usefulness	6.58	0.89

TABLE II: Overview of IMI scores (n=11) [5].

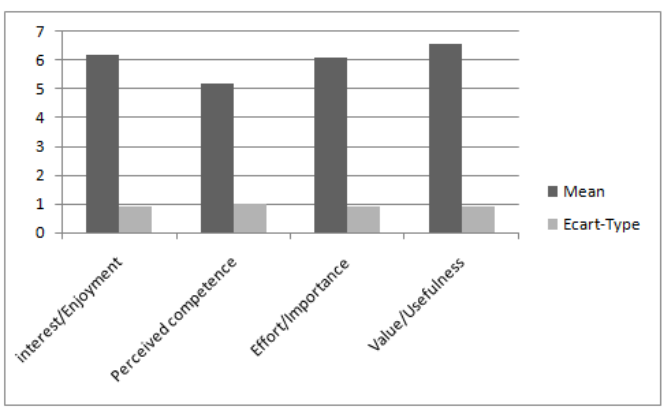

Figure 7. Overview of IMI scores [5].

Discussion

For 11 patients, the score obtained on the SUS questionnaire is 71.81, so according to [8], our system is usable and acceptable in the grade C scale, with a good adjective score. Thus, the average IMI subscores range from 6.09 to 6.58 (out of 7), with the exception of the "Perceived Competence", perhaps due to limited exposure to the system. Participants were enthusiastic and provided promising feedback, highlighting the benefits of the system for hand rehabilitation. Users emphasized the system's positive impact on motor and brain function. Motivation and commitment were observed, with some patients expressing a desire for frequent use.

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The study showed that the system did not require therapeutic support, suggesting partial autonomy for patients undergoing hand rehabilitation after stroke. Despite the positive results, limitations were identified, particularly with regard to the perception of 3D movements in the virtual environment. Patients, often elderly and cognitively impaired, found it difficult to perceive 3D movements, resulting in both motor and brain fatigue.

Conclusion

This article presents a system designed for functional hand rehabilitation, using two VR-based exergames. The games involve harvesting fruit in a virtual grove and incorporate measurements to quantitatively assess the patient's performance. The system uses an innovative approach, relying on artificial intelligence to adapt the game to individual motor skills during rehabilitation sessions. Developed in collaboration with rehabilitation specialists, the system was tested on 11 stroke patients.

Results from subjective evaluations and standardized questionnaires indicate positive feedback on usability and acceptability.

Future improvements aim to include additional hand movements for a diverse range, introduce varied environments for controlled practice, and resolve depth perception issues through verbal cues and VR headset integration for a more realistic experience.

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