VR Training System for Rehabilitation and Compensatory Analysis after Stroke

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ABSTRACT

Stroke is one of the most common diseases that lead to impairment of upper limb dexterity. Nowadays, Serious Games is a common approach to help stroke patient's recovery. However, during motor rehabilitation protocols, it is important to detect compensatory movements, which are not currently handle in most serious games. The lack of compensatory movement detection can lead the patient to learn new and incorrect movement patterns, compromising training sessions. Thus, this paper presents a technique that differentiates real upper limb functional improvements from compensatory movement patterns. To prove our theory, a system has been developed. This system consists of a highly customizable Virtual Reality serious game, with adaptable levels and tasks. Interaction with the game is done through a handle of a robotic platform. This platform has assistance feedback, which can be configured to stimulate or restrict the execution of the movements. In the game, the subject must control a bird of prey to hunt and to run from predators. 3D motion trackers are placed in different points of the subject paretic arm. Through these trackers, it is possible to detect a compensatory movement and to lead back the patient to correctly guide the bird of prey. Therefore, we believe that the proposed method along with the built VR serious game system will be a useful supporting tool for helping both the patient during his training sessions and the therapist for better analysis of movements in conjunction with the definition of more specific stroke rehabilitation protocols.

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INTRODUCTION

In recent years, there were more than 25 million stroke survivors worldwide, and this population is predicted to reach 70 million by 2030 (Feigin et al., 2015). According to the World Health Organization, stroke is the second leading cause of death in the world and occurs predominantly in middle-aged and elderly adults (Oliveira et al., 2020; WHO, 2017). Generally, the most effective recovery occurs in the first three months, with great efficiency of neuroplasticity in the first month (Zeiler & Krakauer, 2013). In these first moments, some functions can be recovered as, for example, the brain edema is reduced, and thanks to the process of early neuroplastic restructuring (Teixeira, 2008). However, despite the large number of existing rehabilitation programs, the complete recovery of motor function, especially of the upper limbs, through conventional therapies, is still a challenge (Langhorne et al., 1996; Tosto-Mancuso et al., 2022).

Therefore, new therapeutic approaches are increasingly concerned with improving sensorimotor evaluative and individualized protocols, which integrate sensory rehabilitation for greater functional recovery of these individuals (Langhorne et al., 1996; Tosto-Mancuso et al., 2022). Among such approaches are serious games and virtual environments, which can promote neuroplasticity by providing task-oriented training, with high repetitions and adjustment of parameters such as therapy time, intensity, and challenges. Rehabilitation through virtual environments enhances brain plasticity when associated with motor, sensory and visual stimuli. Besides, actions intended through the motor goals added to a visual feedback result in an increase in the patient's recovery rate (Heenan et al., 2014).

However, the loss of limb functions requires major adjustments in interactions with the physical world. A common response to this loss after a stroke is to learn compensatory ways of a movement, including using the non-paretic hand. There are also compensatory changes in the coordination of movements of both hands and of the paretic forearm with the trunk (Nakayma et al., 1994; Taub et al., 2014). Some forms of compensation are obvious, but others are subtle enough to go undetected in the absence of sensitive behavioral measures, making them easily confused with real recovery (Levin et al., 2009). Besides the excessive trunk displacement (Levin et al., 2002), motor compensations during reaching have also been described in terms of excessive axial trunk rotations (Levin et al., 2015; van Kordelaar et al., 2012), scapular movements (Robertson et al., 2012), flexor synergy and an abnormal synergistic shoulder and elbow coupling, which permits the patient to lift the arm and bring the hand back toward the body at the same time (Lrvine, 1972).

Methods of quantitative movement analysis have emerged as a means of identifying kinematic patterns that discriminate between upper limbs functional improvements (due to true motor recovery) and those due to compensatory movement patterns (Levin et al., 2002; Murphy et al., 2011; Raghavan et al., 2010; Wade et al., 2014). A method widely used for quantitative analysis of movement is the study based on the analysis of the kinematic synergy of the limbs. In the healthy nervous system, non-pathological kinematic synergies are based on the ability to produce joint movements equivalent to other movements (Yang et al., 2006). However, the pathological flexor synergy is an abnormal linkage between arm joints resulting in limitations when performing a task-relevant movement that may have reduced adaptability (Reisman, 2003; Shaikh et al., 2014; van Kordelaar et al., 2012). Information about the extent to which the damaged nervous system preserves kinematic adaptability is important for therapists to determine the potential for motor recovery after stroke and to design personalized treatment programs to recover specific motor elements related to reaching ability (Levin et al., 2016).

Therefore, researchers and therapists who work in the neurological rehabilitation process with these people are encouraged to develop and apply new methods of interventions or combinations of therapies that promote patient motivation and adherence and are effective, especially in potentiating the recovery of the upper limb functions and motor skills (Langhorne et al., 1996). Thus, new therapeutic approaches are increasingly concerned with improving sensorimotor evaluative and individualized protocols, which integrate sensory rehabilitation for greater functional recovery of these individuals.

An adaptable virtual environment associated to a compensatory movements analysis, can prove to be quite convenient during rehabilitation. In addition, this approach allows individuals to perform specific therapeutic exercises in a pleasant and motivating way without learning inappropriate and harmful compensatory movements for their full rehabilitation (Laver et al., 2012; Thornton et al., 2005). From such perspectives, this article addresses a proposal for an integrated system, aiming to assist in the proprioceptive and motor rehabilitation of subjects with hemiparesis in the upper limbs resulting from a stroke. Furthermore, it is intended to evaluate the adequacy of the developed system as a supporting tool in the rehabilitation processes. It is believed that such approach can also help the therapist in the definition of more specific rehabilitation protocols.

METHODS

The proposed system is composed by a virtual environment and a robotic device, highly customizable, which allows the therapist to adjust rehabilitation protocols according to the clinical condition and evolution of a subject. The system interface, originally, offers equal stimulus and freedom of movements, regardless the motor or proprioceptive capacity of post stroke individuals. Thus, as the motor response depends on each individual functional characteristic, the rehabilitation protocol was adapted by aiming at recovery stages, facilitating motor reeducation and proprioceptive relearning of the affected limb. Therefore, to maintain the proposed environment stimulating and efficient, the rehabilitation protocol established the same set of activities for all participants. However, the parameters that regulate the requirements for carrying out the tasks can be individually adjusted.

Multiparametric Model

The proposed model is divided into three main elements: a robotic platform, a VR serious game and a tracking network. The platform and the game are classified as interface elements, being instruments of motor, proprioceptive and visual feedback. The tracking network act as element for the dynamic adjustment of the serious game. Figure 1 shows the central elements of the proposed model.

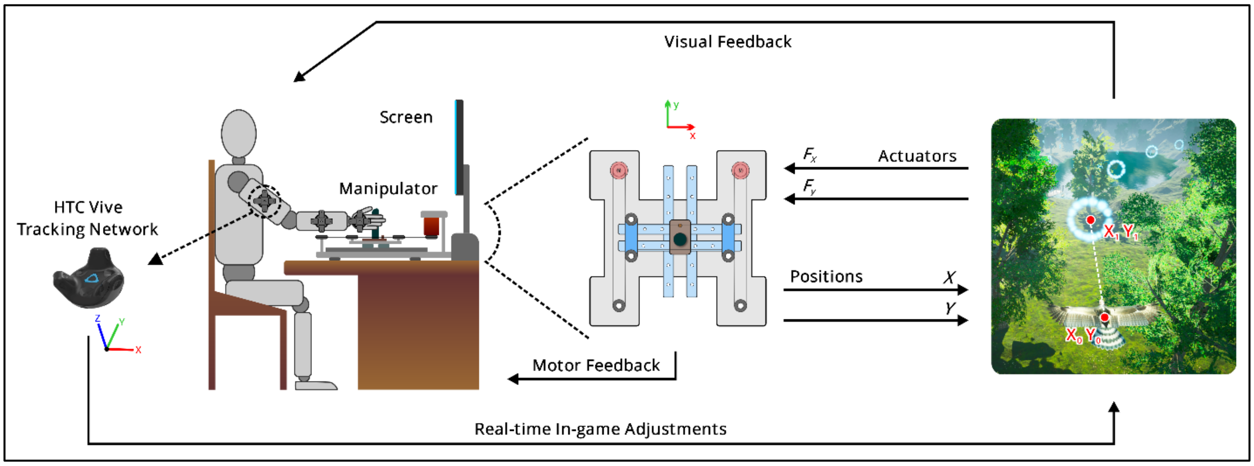


Figure 1. Illustration of the multiparametric model highlighting the game communication with the robotic platform and the tracking network.

During training sessions, the patient interacts with the robotic platform by moving its handle. The positions captured by the platform are sent to the game, which are converted into the bird's movements. The game can also act on the platform through motor feedback, providing the patient a better feeling of control over the bird. At the same time, the outputs of the motion trackers positioned on the hemiparetic limb are captured, which allow the calculation of the joint positions of the shoulder and elbow. By evaluating the estimated trajectory for the bird (in Figure 1: $X_0Y_0 \rightarrow X_1Y_1$) one can define the correct movement of the subject's arm to be performed. That is, from the outputs of the tracking network and the positions of the robotic platform, it is possible to calculate the difference between the angle executed by the individual and the correct angle for that movement (set by the therapist). The resulting difference may be indicative of a compensatory movement performed by the individual. For example, for the bird to turn right and left correctly in the virtual environment, it is necessary to move the handle to the right and left. In this situation, the correct movement of the individual's limb is rotation of the arm with the elbow by about 90°. However, the individual can perform the movement using other ways, considered as compensatory, such as performing a lateral inclination or even an abduction of the shoulder. In these cases, the position of the trackers will be different from the correct position, generating an error in relation to the expected response for the subject's kinematic-motor control. Taking this error as input, the serious game can adjust to, for example, alter the flight path of the bird in the opposite direction to the error, requiring the patient to seek for correcting his posture and movement.

Virtual Environment Interface

To develop the 3D environment, object interactions and animations, we chose *Unreal Engine 4* (*Epic Games™*), using C++ programming language. It is a graphics engine, or set of integrated tools, widely used for building projects related to areas such as games, arts, architecture, and simulation. This technology was used in order to generate a virtual environment with high power of realism and to maintain a good balance with respect to the computational cost (Ratcliffe & Simons, 2017).

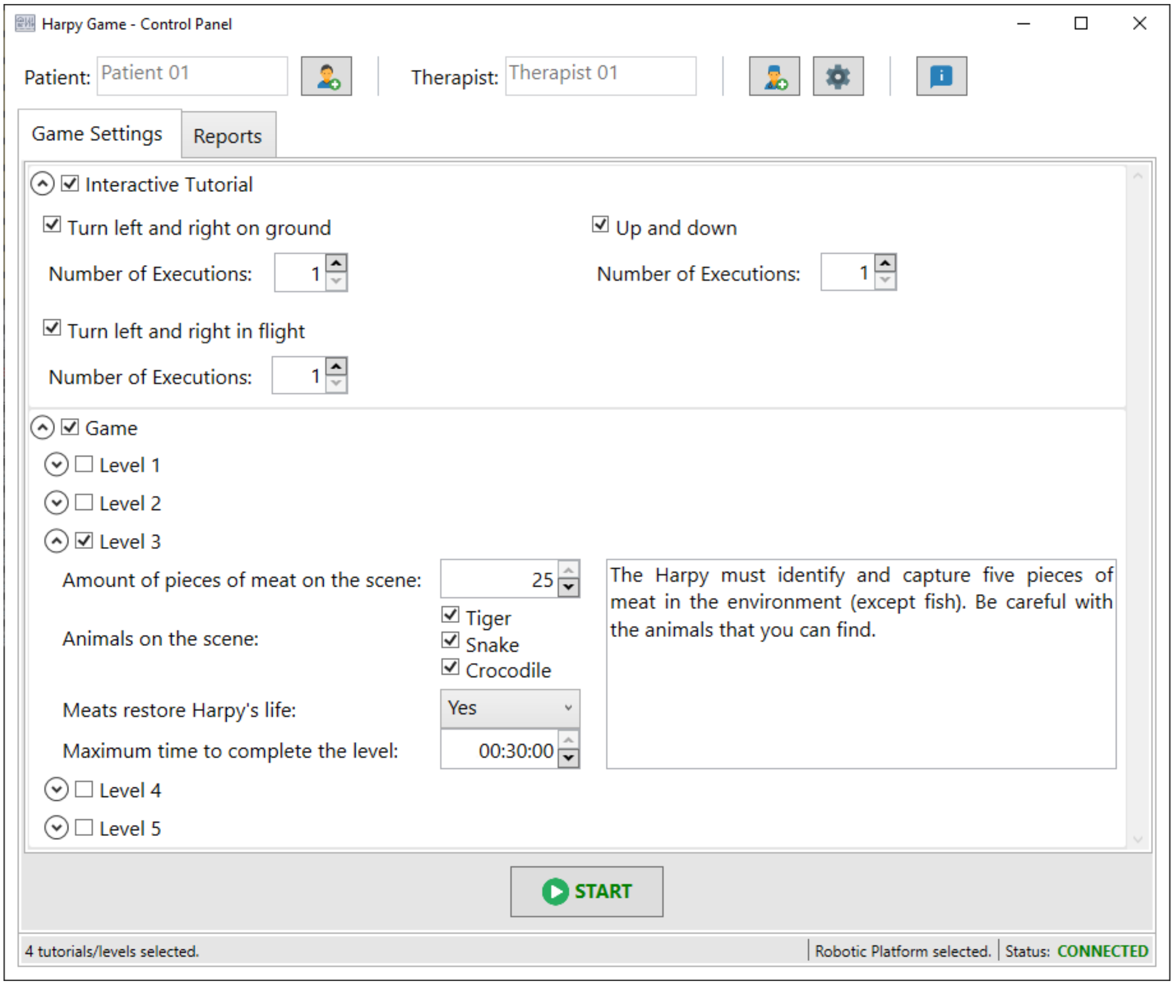
The modeling of objects, such as vegetation and other animals present in the environment, was accomplished by using *Blender 3D* (*Blender Foundation*™), a software widely used for modeling, animation, texturing, compositing, and rendering. The animals were modeled and textured based on real high-resolution photos. Screenshots of the virtual environment can be visualized in Figure 2.

Figure 2. Screenshots of the virtual serious game environment.

The game takes place in a forest, where the subject controls a bird of prey, being able to move freely in different directions and in suitable degrees of freedom, according to objectives and challenges to be met. Initially, three levels were developed in the environment, as well as an interactive tutorial. Each level has different objectives, working on specific movements.

- Interactive tutorial: The subject must follow the direction of some arrows. In this session, arm extension in four directions is trained.
- Level 1: The subject must pass through several rings scattered around the environment. It is necessary to make smooth and firm movements with the arm.
- Level 2: The subject must catch five fish in the lake. The capture must be fast and accurate, working with elbow flexion and extension.
- Level 3: The subject must capture five pieces of meat, while running away from predators. This level works on motor and visuospatial coordination, proprioception, and reaction speed.

The system also comprises a control panel, where the therapist can register, change, and consult subject's data, configure the general parameters of the virtual environment, select the levels in each session and configure the challenges for each of them. Figure 3 shows the main screen of the control panel. In this way, it is possible to create a customized execution protocol, configuring the sessions according to the therapeutic needs of each patient.



Patient: Patient 01

Therapist: Therapist 01

☑ Interactive Tutorial

☑ Turn left and right on ground
Number of Executions: 1

☑ Up and down
Number of Executions: 1

☑ Turn left and right in flight
Number of Executions: 1

☑ Game

☐ Level 1
☐ Level 2
☑ Level 3

Amount of pieces of meat on the scene: 25

Animals on the scene: ☑ Tiger ☑ Snake ☑ Crocodile

Meats restore Harpy's life: Yes

Maximum time to complete the level: 00:30:00

The Harpy must identify and capture five pieces of meat in the environment (except fish). Be careful with the animals that you can find.

☐ Level 4
☐ Level 5

4 tutorials/levels selected. | Robotic Platform selected. | Status: CONNECTED

Figure 3. Control panel interface, with a session being configured.

In the defined training protocol, the difficulty is gradually increased by the therapist, without discouraging the subject. Thus, as the participant evolves, completing the challenges with greater ease, the therapist modifies the parameters of each level for the next executions, consequently, adjusting the rehabilitation behaviors through the clinical evolution.

Several parameters can be changed during executions, namely:
1) Number of levels available.
2) Execution time of each level.
3) Shape of challenges, size of objects and amount in the scene, damage indication and bird recovery.
4) Bird speed (displacement of the bird in relation to the scene).
5) Precision of movement (displacement of the bird in relation to the rotation on its own axis).

The modification of each parameter is correlated with the difficulty defined by the therapist, which directly depends on the patient's condition. All challenges were designed considering the improvement of motor and proprioceptive function recovery in the hemiparetic upper limb. Table 1 shows each adjustment variable and their respective parameters, as well as their relationship with the therapeutic goals of post-stroke rehabilitation of the affected upper limb.

Table 1. Adjustment variables and their respective parameters, associated with the levels and their possible correlations with the therapeutic goals of rehabilitation.

Variable	Parameter	Level	Therapeutic Correlation
Time	0 to 30 minutes	All	The adjustment of the maximum time for each patient can be used to verify the measure of ability, determined by the relation of speed and performance of the task in time, in this way it is possible to determine the rate of learning and accuracy of the movement in each level. Thus, the shorter the time the greater the positive impact on rehabilitation.
Rings size	Large/Medium/Small	1	The size of the rings is related to the precision of the movement performed by the patient in the level. The smaller the ring diameter, the greater the accuracy required.
Bird speed	0 to 25 m/s	All	The bird speed is strongly related to the dynamics of execution of the movement and the time directed to the execution of the objectives of the level. With faster speed, the precision of the movements tends to decrease and, therefore, in the initial phase of rehabilitation, a medium to low speed is indicated, such as 10m/s (considering that the total size of the scenario is 1000m²).
Challenges to overcome	44/33/22 rings	1	During the three levels, the greater the number of goals, the greater the time spent and, consequently, the greater the number of repetitions of movements that the individual must perform, which include the repetition, intensity, and specificity of the task.
	5 fish	2	
	5 pieces of meat	3	
Damage	Yes/No	2 and 3	When approaching predators or touching obstacles such as trees, the subject will receive damage feedback on the bird, which may or may not be activated by the therapist. Likewise, when capturing food, it will be possible to activate the bird's health recovery. These feedbacks are important to encourage the patient to perform the movement in an assertive and coordinated way. This is due to the greater activation of tendon and muscle sensory receptors, whose objective is to increase position awareness, adjust reaction time and coordination of movement by the limb.
Bird recovery	Yes/No	2 and 3	
Animals in the scene	Yes/No	2 and 3	
Controls precision	1 to 10	All	The manipulation precision of the controls is related to the minimum and maximum angle of flexion and extension of the arm. This option can be customized according to the motor response of each patient. In this way, the therapist can configure the dosage of assistance or resistance to movement. That is, the greater the assistance provided by the robotic device, the less muscle activation will take place.

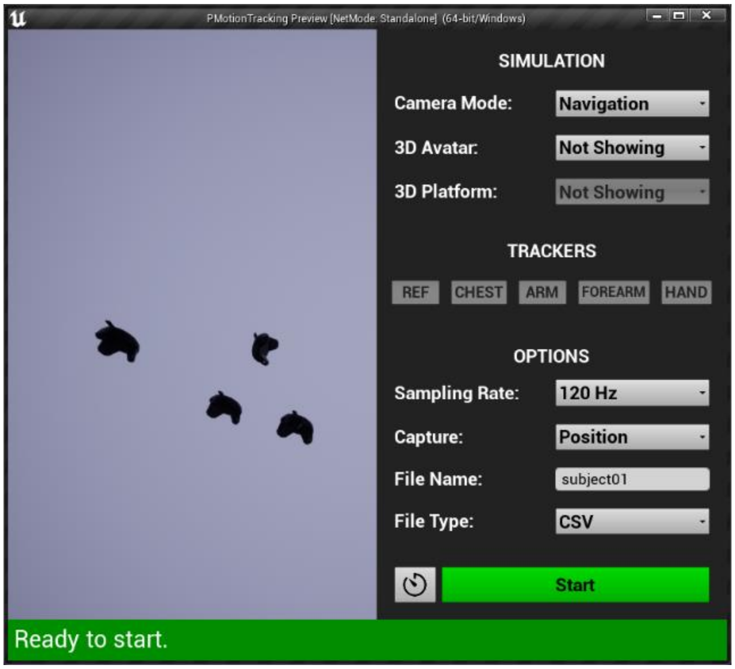
Control System

For the control interface, we built a platform for assisted support. Based on the *H-Man* model (Campolo et al., 2014), the platform has a mechanism composed by two motors driven by cables acting in a Cartesian plane. In this mechanism, the individual performs a movement through a rod attached to a rail connected to the cables. These cables activate the motors which return assistance feedback. The therapist can configure this assistance to generate an elastic force in the patient's arm, helping him in the execution of the movement, or restrict the movements to require greater muscle activation.

The dynamic drive of the motors is made by an *Arduino*, which controls the movement of the X and Y axes, and can even generate diagonal movements, increasing its range. The algorithm developed in *Arduino* generates an output data set containing the current X and Y positions and the force generated by the two motors, sending this data to the computer, through a serial port COM (Costa, 2019).

Movement Detection

To capture hemiparetic limb movements, we use a network of motion trackers developed by *HTC™ Vive*. The *Vive* tracker is a disc sized wireless tracking unit that can be attached to any objects to bring full body tracking to a whole new level. The trackers can be attached to body members, like arms and legs, or to any object to be brought into the VR realm. Each tracker converts infrared signals emitted by the *Vive Lighthouse* (small reflection stations positioned in the real environment) into 3D position and sends it back to the PC either via USB or a wireless dongle. The trackers were designed to be used in conjunction with the *HTC™ Vive* VR headset. However, it is entirely possible to use the trackers autonomously.



Camera Mode: Navigation
3D Avatar: Not Showing
3D Platform: Not Showing
Sampling Rate: 120 Hz
Capture: Position
File Name: subject01
File Type: CSV

Ready to start.

Figure 4. Motion trackers module interface.

We use five trackers positioned on the subject's chest, arm, forearm, and hand, as well as a tracker used for reference. The tracker positioned on the chest aims to identify possible compensatory movements related to the anterior and lateral trunk. The trackers positioned on the arm and forearm have the function of identifying compensations related to shoulder abduction and elevation, trunk rotation, scapular movements, and other abnormal synergies. The hand-positioned tracker aims to synchronize the positioning of the hand with the platform handle. Finally, the reference tracker has the function of defining the correct positioning of the entire sensor network and must be positioned in front of the patient, at a fixed point on the table. To enable the motion capture, we developed a module in *Unreal Engine 4* that implements all these functions and, during the sessions, analyzes and sends all movements captured by trackers to the game, as well as saving them to a file. Through this module, it is possible to visualize the position of trackers in real time and configure captured options, such as sampling rate, data to be captured, file name and type and number of trackers. It is also possible to configure simulation options such as camera mode, displaying a virtual avatar with each sensor in the 3D scene, and displaying the 3D model of the platform for real-time virtual avatar interaction. The saved file can contain both position and orientation of each of the configured trackers and can be saved in CSV or TXT format. Figure 4 shows the software interface.

RESULTS

As preliminary experiments, tests were performed with three healthy volunteers, positioned in front of the platform, observing the initial angle of 90º of the elbow. The measurements of the right upper limb of each patient were taken, defining the central point of the arm and forearm, as well as the correct position referring to the sternum in the volunteers' chest and the correct position of the hand. The trackers were properly positioned at the defined points. Figure 5, on the left, shows the execution of the system by a volunteer using the platform, but without the use of trackers, for better visualization. And on the right, we can observe the execution of the system with a volunteer using the trackers and the capture module.

Figure 5. Execution of the system using the robotic platform and the motion trackers.

In this initial test, the first level is performed, where elbow flexion and extension are worked by passing the bird of prey through scattered rings around the virtual environment. In the test protocol, all the variables detailed in Table 1 were configured through the developed control panel. Three five minutes-sessions were performed for each volunteer. The positioning data of the platform (X and Y) and the trackers (X, Y and Z) were captured at a frequency of 120Hz. In the first session, we instructed the volunteers to perform all the movements correctly, always observing the therapeutic correlation of each movement. In the last two sessions, we induced the volunteers to perform some compensatory movements. In the second session, when controlling the bird of prey up and down, the volunteers performed compensatory movements of the anterior and lateral trunk. And in the last session, when it was necessary to guide the bird to the left and right, the volunteers performed shoulder elevation and abduction.

During the game, when any of these compensatory movements is identified by the tracker network, the bird remains in its original position, not performing the correct movement. For this identification of the compensatory movement, a threshold was defined for each sensor in the system. Thus, in the first session, the path was followed correctly, but in the second session, when the volunteer tried to move the bird up and down, the system identified the trunk compensations and did not allow the bird to move in the environment. The same occurred in the third session, not allowing the bird to move left and right, when shoulder abduction compensation was identified. The data captured by the sensors and used for this analysis were plotted in line graphs for visualization and comparison.

In the line graphs, the position threshold is represented by the yellow dotted line, and the moments where the threshold is reached, causing the bird to reset its position, are represented by the red parts. Figure 6 shows the X-axis positions of the chest trackers captured during the session where no compensatory movements were performed (a) and the session where compensatory movements of a volunteer's anterior trunk were performed (b). It also shows the Z-axis positions of the arm trackers captured during the no compensation session (c) and the session where compensatory shoulder abduction movements of a volunteer were performed (d). When comparing them, it is possible to observe the oscillation of the thorax movements in the moments when it was necessary to descend and ascend the bird in the environment, as well as when it is necessary to control the bird to the sides. In these moments, the bird remains in the valid initial position, not obeying the commands until the correct movement is performed, as shown in the images to the right of the line graphs, with the volunteer performing the movements and the game correctly reflecting them on the bird.

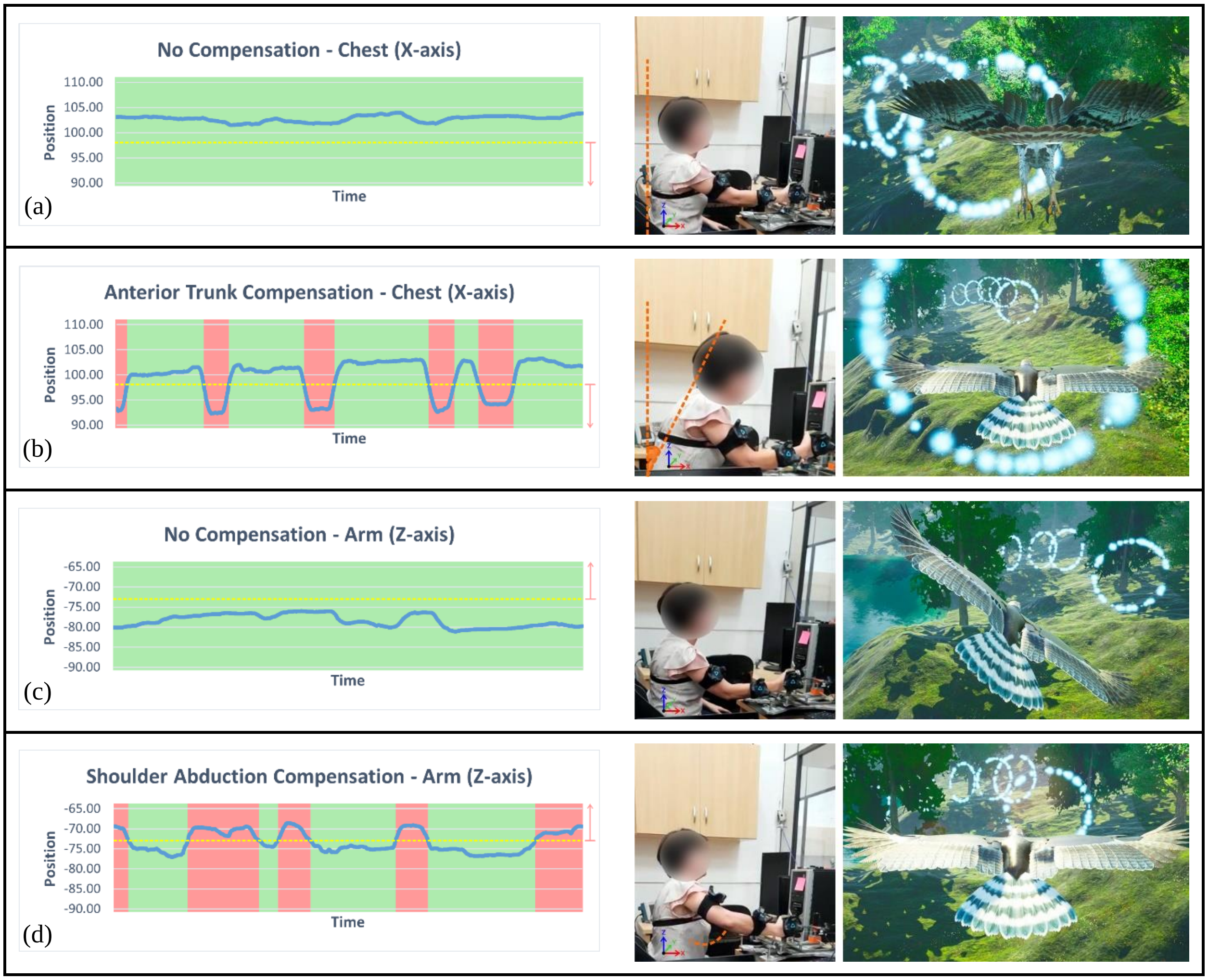


Figure 6. Positions related to the X axis of the chest tracker and the Z axis of the arm tracker (left), and the movements performed by the volunteer reflected in the game (right).

A good adhesion of the volunteers was observed during the sessions, having pleasant and smooth controls, and allowing more repetitions of movements. Other rules can be defined when detecting compensatory movements, such as applying a counterforce to the platform motors, requiring the volunteer to correct his posture and movement.

CONCLUSIONS

Results have shown that the proposed integrated system can be of great value for the stroke rehabilitation process. In particular, when it is performed using highly adjustable environments that respect individual limitations. This can offer tools to help stroke therapist in analyzing the evolution and results during treatment. Through our serious game, working with the robotic device and the tracking network, it is possible to monitor the clinical evolution of the volunteers, by evaluating compensations in the affected upper limb compared to the healthy one.

Also, our robotic therapy encourages high repetition of movements with minimal supervision in a highly motivational environment for somatosensory rehabilitation, handling principles of conventional therapy. The device is easy to configure and allows movements in different degrees of freedom, requiring minimal supervision from the therapist. In addition, it is possible to assess motor performance and to configure the dosage of assistance or resistance to movement.

The tracking network has shown to be very promising for detecting compensatory movements. Based on the detection rules defined by the therapist, the system was able to adjust the game, in real time, according to the type of compensation identified, as well as apply admittance and impedance forces through the robotic platform. Thus, with therapeutic assistance, the individual is led to correct his posture so that the movements are performed correctly.

We aim to use this system as a method of future stroke rehabilitation, since more efficient exercises can be offered to a larger set of engaged individuals. As future work, we intend to couple a patient muscle-skeleton model in the system to analyze muscular activation over a stroke recovering session. This can help a deeper diagnosis since the analysis shall be more complete with the identification of which muscles are activated during a compensatory movement.

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