Design and implementation of a Virtual Reality platform for Upper Limb rehabilitation

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Resumen

Robot-aided and virtual reality environments are used usually in rehabilitation tasks due to their high effectiveness. Furthermore, these technologies can be used as rehabilitation exercises complementary to the traditional ones. In fact, combining these two types of rehabilitation allows patients to receive more quantity of therapy. The use of serious games enables patients to feel more motivated and increase the engagement to the treatment and the level of attention during the motor rehabilitation process. Therefore, these therapies can improve motor learning and functional mobility in patients with motor impairments.

In the rehabilitation process proposed by mean of serious games, patients feel a haptic feedback for exercising the arm muscles strengthening. Consequently, the system provides to the patient a total immersion sensation in the serious games. To test the serious games and to check the usability of the platform, a proof of concept was made. The study was carried out for obtaining data which supports the feasibility of the platform developed and to examine if spinal cord injured patients have the ability to manipulate the applications in a successful way.

1. Motivation

Spinal Cord Injury (SCI) is one of the most important neurological diseases that produce deficiencies in the field of physical disability [1]. The arm and hand are designed to perform very skilled movements which allow us to perform daily living activities [2]. The recovery and rehabilitation of the upper limb (UL) after cervical SCI depends on the injury level and severity.

The use of new technologies in the rehabilitation field has been increased in the last years, because patients can increase the therapy. One of them is the Virtual Reality (VR) applied in rehabilitation therapies. There is evidence that VR, in combination with traditional rehabilitation, produces an acceleration in the rehabilitation process and patients enjoy more the task performance [3]. The combination of robotics with VR has many advantages for intervention, such as enabling the grading of activities, obtaining precise performance measures, providing a safe environment, and being enjoyable and motivating.

Integrating gaming features into VR environments has been reported to enhance motivation in adults undergoing physical and occupational therapy [4]. This is called serious game, which is a computer-based game with the goal of education and/or training in any form, as opposed to traditional computer games, which are primarily intended to entertain. Therefore, by using game mechanics it is possible to create an engaging experience that simultaneously helps rehabilitation.

2. Enabling technologies

The system makes use of a low-cost haptic robot the Novint Falcon [5]. This device has 3 DOF (see Figure 1) and it is used to simulate touch in a virtual world, allowing the user to feel virtual objects or other physical forces. The device consists of three motorized arms attached to an interchangeable end-effector. Due to its low cost and features, the Novint Falcon could be an excellent tool used with a rehabilitation purpose. The device can be used as an end-effector robotic device for UL rehabilitation to assist, resist or support the patient. The main advantage of the end-effector system is that it adapts to patients with different body sizes. It has 10x10x10 cm^3 of 3D touch space and can exert up to 9 Newtons of force. The device can simulate the feeling of objects to a sub-millimeter precision and refreshed to 1000 Hz, making the experience very smooth.

For using this device with a rehabilitation purpose, the standard grip, with ball shape, needs to be changed. This spherical end-effector is difficult to use for patients with neuromotor disabilities. After some discussions with occupational therapists, a cylinder grip was designed for a better hand-grasp.

The design for the prototype was made to be built in a 3D printer (see Figure 1). It was designed considering an average of the distance from the palm of the hand till the end of the fingers.

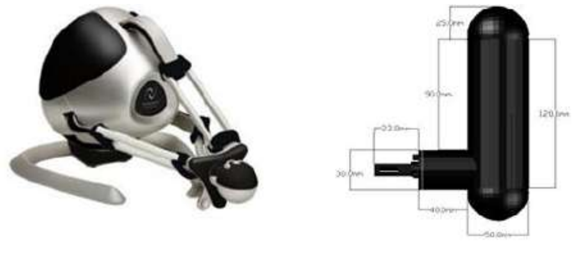

***Figure 1.** Novint Falcon haptic device and the novel HandGrip designed for Novint Falcon*

3. Implementation

Rehabilitation is a special environment for games, therefore, specific design considerations should be made. The design needs to ensure that the game aspect does not compromise the rehabilitation effort.

3.1. Design consideration

In these types of games, the task to develop must be adjustable and personalized for each patient, because they must not create stress. In rehabilitation, exercises are necessarily simple. They need to be easy to repeat, to ensure that the movement is correct and beneficial for the patient [6]. Furthermore, each exercise needs to have very clear goals and limitations. To promote plasticity, exercises need to encourage a constant repetition of movements. Objectives must be achievable performing simple movements. With all these considerations, the patient is involved in a learning process.

For this paper, virtual sessions were designed along therapeutic guidelines for SCI interdisciplinary rehabilitation. The system offers visual, auditory and haptic feedback during the sessions, to increase the engagement, to facilitate the comprehension of exercises and to deliver a clear sense of progress.

3.2. Modular design

The entire platform is made of different modules implemented in Unity 3D [7]. These modules are used in all the games with different variations between them.

Virtual end-effector. This module updates the position of the end-effector every frame in the scene. This is very important for obtaining a good visualization in the game. It is necessary to avoid vibrations of the image or unreal movements.

Collision detection. This is the key of these rehabilitation games. The collision detection between the end-effector and the game objectives must be done in all the games.

Timer. All the games need a timer to restrict the therapy duration. Therefore, patients are focused on the task because they have only a certain time to perform it.

4. Serious games

The rehabilitation platform is formed by three serious games (see Figure 2). The goal of all of them is to reach the number of objectives selected by the therapist.

Figure 2. *Interface of "Following the path", "Picking bananas" and "Destroying stars" games*

4.1. Following the path

The end-effector in the scene is representing a pencil. When the user moves it, the pencil draws a trajectory in the scene. The visualization of the trajectory helps users in the development of the task. Users must go by the path without going out of the edges. When users go out of the trajectory, a sound is produced to enhance their attention and a force is exerted on the opposite direction. The goal of the game is to pass through all the lines. When the user completes a segment, it changes its color to a darker one (see Figure 2).

This rehabilitation game is based on a path guidance exercise. The therapeutic objective is to improve the accuracy in the UL movement made by the patient and to recover fine motor control. This training modality using robot-mediated therapy is a combination of assistive and active exercise. The force applied in this rehabilitation game is convergent [8]. The assistive force pushes the patient's hand to the correct path.

4.2. Picking bananas

The end-effector in the virtual environment is visualized as a basket and the objectives to achieve are bananas. The goal of the game is to pick up the total number of bananas with the basket. Therefore, users need to move the end-effector in a precise way to capture the bananas. The game finishes when all the bananas have fallen from the trees.

Four banana trees appear in the scene with the total number of objectives selected in the game setting menu. Each banana is going to fall from the trees in a randomly order, preventing users from knowing in advance the position to which they must move the end-effector (see Figure 2).

Depending on the number of objectives and time chosen, the frequency of falling changes to obtain a proportional distribution. When one banana is going to fall, it changes its color and a sound is produced. These visual and auditory feedbacks help users to identify toward which place they need to move the end-effector. When users catch a banana with the basket, it disappears, and another sound is produced to inform about the achievement.

The force feedback increases with the number of bananas captured, but if the number is high this can tire users, then the option to release the basket weight appears. Every five bananas collected, the user can perform the release of weight in a corner of the screen. In this way, the basket will be empty again and the force feedback will be zero till a new banana is captured.

The rehabilitation exercise implemented in this serious game is resistive, that means that the haptic robot makes the movement more difficult by opposing the movement received from the patient. Progressive resistance exercise appears to be a safe and efficacious intervention for many patients with muscle force deficits.

4.3. Destroying stars

The aim of this game is to destroy all the stars that appear in the scene. To achieve it, the user needs to move the end-effector, a rocket on the screen, till the star position.

The game finishes when the total number of stars are destroyed or the time is up.

At the beginning, the objectives selected in the game setting menu appear in the scene and the end-effector appears in centered position on the screen. The stars have different size to force the user to go away from the center. The bigger ones are easier to catch than the smaller ones.

During the game, if a collision is detected between the rocket and one of the available stars, this star will be destroyed and will disappear of the scene. When the user destroys a star, a sound is produced and the score available in the screen increments. This feedback source helps to the patient to follow their own progress during the performance.

After destroying a star, the user must come back to the center of the screen before other destruction. The collision detection will not be available until the user reaches the center of the scene. To make this case clearer, once a star is destroyed the Earth, that is placed in the center acquires a colorful appearance. When the collision of the rocket with the Earth has occurred, the user can go again for another star and the Earth becomes transparent (see Figure 2).

In this case, there is a zone without force in the middle of the game circle, but when the patient is close to the targets, the force applied increases. Its goal is to obtain the strengthening of the UL muscles. In addition, the linearity of the movement can be checked with this game.

5. Proof of concept

To test the three serious games and to check the usability of the platform, a proof of concept was made in the Biomechanics and Technical Aids Department of the Hospital Nacional de Parapléjicos in Toledo (Spain). The study was carried out for obtaining data which supports the feasibility of the platform developed and to examine that SCI patients have the ability to manipulate the applications in a successful way.

5.1. Participants

Eight people have participated in the platform validation, four healthy subjects and four cervical SCI patients, obtaining paired groups. All SCI patients were neurologically assessed by means of ASIA (American Spinal Injury Association) scale (grades A-E), being all the cases incomplete injuries in both motor and sensitive aspects. All patients involved in the study need to have control of their UL including shoulder and wrist movement allowed.

Patient	Age	Sex	Injury	ASIA	Etiology
P1	19	M	C4	C	Trauma
P2	18	M	C4	D	Trauma
P3	45	F	C5	D	Trauma
P4	20	M	C6	C	Trauma

***Table 1**. Clinical characteristics of the SCI patients' sample analyzed*

In Table 1 the clinical characteristics from all SCI patients are shown. In relation to the healthy subjects, the mean age was 33.25 years and the 50% of the sample analyzed was female sex.

5.2. Intervention

The study was performed for two days, with two sessions per day. The three games were performed in all sessions, always in the same order and with the same characteristics to avoid including variability into the study.

The study was carried out only taking data from one of the arms of the participants. In the SCI group, the arm with less mobility was selected. It was the same member in which they were receiving traditional rehabilitation in physiotherapy sessions and the one in which they wanted to improve their skills. In the healthy group, all subjects were right-handed.

5.3. Processing and analysis

In this study, to analyze the trajectory smoothness is one of the key aspects. Movement smoothness is a quality characteristic related to the continuity of a movement, independent of its amplitude and duration [9].

SCI patients' goal-directed reaching movements are saccadic, which become smoother with motor recovery, because muscle properties contribute to movement smoothness. Measurement of smoothness may provide a meaningful, objective quantification of motor performance that could be used to augment clinical evaluations. Consequently, movement smoothness has been used as a measure of motor performance of both groups healthy and SCI.

Smoothness measures have been obtained using the number of peaks method, which relies on the fact that the speed profile of smooth movements has a single peaked, while unsmooth movements have higher number of speed peaks. Therefore, fewer peaks in speed represent fewer periods of acceleration and deceleration, making a smoother movement. This measure counts the number of local maxima (peaks) of the signal in a given speed profile v(t), where | . |, represents the cardinality of a set.

$$NP \cong \left| \left\{ v(t), \frac{dv(t)}{dt} = 0 \; and \; \frac{d^2v(t)}{dt} \right\} \right|$$

6. Results

In this section, the results obtained in the "Following the path" game are described. SCI patients performed the task slower than healthy people, detecting significant statistically differences between both groups in the performance time ($p<0.05$) (see Table 2) by the application of Kruskall Wallis non-parametric test.

The trajectory analysis in terms of smoothness show difference between healthy and SCI patients. In all cases, SCI patients execute a higher number of corrections within the trajectory (see Figure 3) and, as a consequence, a higher peaks number in the speed profile than healthy subjects.

The boxplots related to the peaks number are shown in Figure 4. The boxplots aren’t overlapping for both groups, discriminating between pathological and healthy condition.

	Healthy subjects (n=4)	SCI patients (n=4)
Duration (s)	**28.55 (7.91)**[a]	**49.52 (13.33)**[a]
Mean velocity x (m/s)	0.063 (0.008)	0.058 (0.015)
Mean velocity y (m/s)	0.070 (0.018)	0.058 (0.020)

Table 2*. Duration and mean velocity during the execution of “Following the path” game (a, p<0.05)*

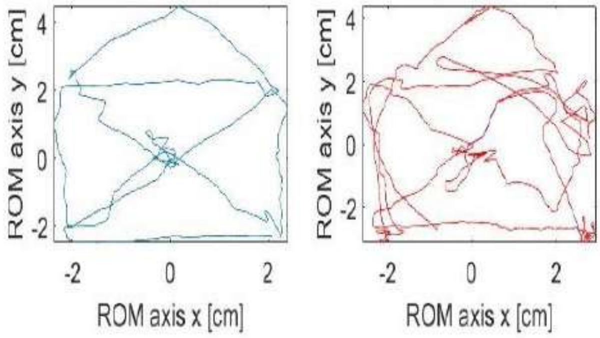

Figure 3*. Trajectory performed by a healthy subject (blue color) and a SCI patient (red color) during the “Following the path” game*

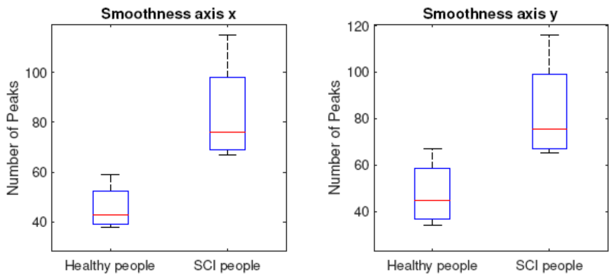

Figure 4*. Boxplot related to smoothness characteristic in healthy and SCI patients’ groups during the game “Following the path”*

7. Discussion

This work takes advantage of low-cost VR systems and robotic haptic devices to enhance involvement and engagement of patients, to provide a congruent multisensory afferent feedback during motor exercises, and to benefit from the flexibility of virtual scenarios for adapting the motor exercises to the needs of the patients. Moreover, with this platform, SCI patients can increase the therapy time that spends in their rehabilitation process, which becomes more enjoyable and motivated.

The results obtained confirm the hypothesis of the smoothness analysis, because a higher peaks number indicate a less smooth trajectory. This effect has been observed in SCI patients that perform longer trajectories with more directional changes than healthy subjects. However, there is no evidence of similar experiences in SCI populations and the results can’t be compared.

8. Conclusion

The results show that incorporating technologies into the UL rehabilitation program of cervical SCI patients is feasible, and that the platform allowed collect objective data for checking the SCI patients’ progress.

As a conclusion, this platform can be a perfect complement to the traditional rehabilitation methods. The following step is to program a therapy based on the use of these games with Novint Falcon and to examine the UL functionality improvement in the patients.

Acknowledgments

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