Virtual Reality to Assess and Treat Lower Extremity Disorders in Post-stroke Patients

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Keywords
Virtual reality exposure therapy, stroke, gait, feedback, physical therapy modalities

Summary
Introduction: This article is part of the Focus Theme of Methods of Information in Medicine on “Methodologies, Models and Algorithms for Patients Rehabilitation”. Objectives: To identify support of a virtual reality system in the kinematic assessment and physiotherapy approach to gait disorders in individuals with stroke.
Methods: We adapt Virtual Reality Rehabilitation System (VRRS), software widely used in the functional recovery of the upper limb, for its use on the lower limb of hemiplegic patients. Clinical scales have been used to relate them with the kinematic assessment provided by the system. A description of the use of reinforced feedback provided by the system on the recovery of deficits in several real cases in the field of physiotherapy is performed. Specific examples of functional tasks have been detailed, to be considered in creating intelligent health technologies to improve post-stroke gait.
Results: Both participants improved scores on the clinical scales, the kinematic parameters in leg stance on plegic lower extremity and walking speed > Minimally Clinically Important Difference (MCID).
Conclusion: The use of the VRRS software attached to a motion tracking capture system showed their practical utility and safety in enriching physiotherapeutic assessment and treatment in post-stroke gait disorders.

1. Introduction
Clinical principles, technological devices and safety issues associated with the use of virtual reality (VR) in medicine have been widely discussed [1]. The VR rehabilitation treatment includes the use of computer-based programs designed to simulate real-life events [2], among other uses. Deficits in gait limited functionality in individuals who suffered a stroke and many of them who recovered ability to walk without physical assistance are still disabled by their slow walking speed and short distances walk [3]. Several authors have addressed the use of VR systems [4–11] in recovering the function of the plegic lower extremity (LE), obtaining satisfactory results in the increase of gait speed [4–6, 9–11], cortical re-organisation [6], balance [9, 11] and kinematic parameters [8, 9], most of which were based on an immersive VR system.

The therapeutic approach offered by these systems is very interesting, but not all of them have the ability to evaluate analytical kinematic movements of the joints. Many authors have used kinematic assessment different from the VR systems used as 3D kinematic gait analysis [12]. This type of evaluation is essential to assess functional gait of improvement after a therapeutic intervention. However, the patient needs a more immediate knowledge of performance (KP) and knowledge of results (KR) feedback of different tasks proposed by the physiotherapist to improve motor learning. A kinematic evaluation during the performance is important in assessing improvements of the quality and precision of movement. Furthermore, the physiotherapist needs a real feedback on how the patient is performing the tasks. Once deficits have been individualized, it is important to develop an analytical work involving selective tasks and this analytical kinematic evaluation constitutes an interesting feedback.

The results obtained by using a VR-based system with the software of Virtual Reality Rehabilitation System (VRRS) coupled to a motion tracking in the assessment and treatment of arm motor deficiency after stroke, were satisfactory [13–15]. At the same time, we experimented with the use of a system of this kind in order to study its effects on the kinematics of LE movement in the restorative process after stroke.

In this case series, the intervention with reinforced feedback in virtual environment (RFVE) was described. The aim of the present study was to improve kinematics and motor function (especially gait speed).
2. Methods

2.1 Cases Description

The first participant (participant 1) was a 58-year-old man with left hemiparesis diagnosed from an ischemic stroke (posterior limb of the right internal capsule, corona radiata) 4.5 months prior to evaluation. Before the stroke he exercised regularly and after being discharged his physical limitations became evident. The second participant (participant 2) was a 49-year-old man with hemiparesis after a hemorrhagic stroke (left cerebellar intraparenchymal and paraventricular) three months prior to evaluation. He completed a physical therapy program before recovering good functionality in activities of daily living (ADL), but used a wheelchair for long trips. Our program involves increasing walking speed and stability, improving kinematics and avoiding the misuse of compensation. The scores obtained for both participants in the evaluation pre are presented in Table 1.

2.2 Intervention

We evaluated gait speed by 3MWT (3 Minute Walking Test) and kinematic parameters in the flexion-extension movement of the knee in the single support of the plegic LE, altered sequence in the post-stroke gait. Two evaluations were performed. The first one took place before the beginning of the 15 treatment sessions. The second one was performed the day after the last treatment session.

Our equipment included a high-resolution LCD projector which displayed the virtual scenes on a large wall screen and a computer workstation connected to a 3D motion-tracking system (Polhemus FASTRAK® 3Space, Vermont, USA). The features of the FASTRAK® system were: static accuracy of the position signal 0.76 mm RMS and 0.15 degrees RMS for orientation; resolution of 0.0005 cm/cm and 0.025 degree/degree of range; latency of 4 ms unfiltered from the center of the receiver measurement period up to the beginning of the transfer from the output port. The sampling rate was 120 Hz divided by the number of receivers. The electromagnetic sensor was positioned at different locations on the patient’s leg. The physiotherapist could create numerous virtual tasks for the leg through the use of flexible software called VRRS (Khymeia Group, Italy), originally developed at the Massachusetts Institute of Technology (Cambridge, MA, USA), which processes data coming from the motion of the sensor. He could select the complexity of the motor tasks according to each participant’s LE deficit previously specified. VRRS enables us to visualize additional virtual objects to increase the complexity of motion. So, participants were given information about their leg movements during the performance of motor skills (KP) based on the movement of the sensor virtual representation. The ideal movement and trajectory could also be displayed in the background of the virtual scene in order to facilitate the subject’s perception and adjustment to motion errors (learning by imitation) [16]. Moreover, the KR (spatial error, speed and submovements) regarding the achievement of a requested motor task was given to participants in the form of standardized scores along with an augmented sensory feedback when the score surpassed a predetermined threshold (Figure 1).

Participants received VR treatment one hour daily (Monday to Friday) in addition to the one-hour conventional physiotherapy program, for a total of three weeks (15 sessions). Both therapies were focused on LE motor rehabilitation. In the RFVE program, the subject was asked to perform different tasks; as an example, trajectories were designed with a starting point and an ending point and participants moved the virtual object following the trajectory. If they did not complete the entire circuit, the auditory feedback was not provided. In addition, if during this practice the distance of the trajectory diverged from the range of position marked, the sound became louder as it got further away (auditory feedback) and an object which simulated sensor location changed color (visual feedback) (Figure 1).

The exercises could be more complex by placing a sensor on the top part of the torso. This sensor was simultaneously connected to the heel sensor so that if the patient tried to compensate by flexing his torso during leg movement, the ball deviated from the marked path. This last point was important in order to improve motor control (during the final stage of support, the hip has to stay extended and, at the same time, it is important to improve the strength of the ankle). The physiotherapist continuously interacted with the system and modified all the above parameters based on the participant’s potential to make progress. Participant 2 was asked to use his healthy foot to reach reference points on the ground in order to work on the proprioception of the supporting plegic foot. The distance between the points was progressively increased. To avoid visual compensation, the participant was asked to look at the screen and not his foot after several repetitions (greater attention to the intrinsic proprioception process), making it harder to locate points exponentially high off the ground. Different elements were introduced in the real world and these were reflected in the virtual surroundings to partially modify the exercise so that the participant would be able to achieve new challenges (high steps, etc.). Trajectories were plotted in such a way so that the participant had to touch different objects located at different heights. So, tactile feedback was obtained when touched with the healthy toe (Figure 2).

<table>
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<th>Table 1 Synthesis results</th>
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<td><strong>Participant 1</strong></td>
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3. Results

The percent improvement was calculated using the next formula: \((\text{post} - \text{pre})/\text{(pre)} \times 100\).

Both participants reported an improvement in balance and functionality in difficult tasks. Participant 1 was able to run at a higher speed and started to play sports that he used to play such as tennis and increased his walking speed of 11\% (0.16 m/s) in the 3MWT. Whereas, participant 2 managed to leave the wheelchair that he used for long journeys on stable ground and improvement was 41\% (0.34 m/s) in the 3MWT.

In the kinematic parameters, the speed reached in exercise did not vary significantly in both participants; however, variations were present in spatial error (SE), thus indicating how much the participants deviated from the trajectory and the mean number of submovements (or speed peaks, the greater amount of submovements the choppier and less fluid the movement became). Patient 1 experienced a decrease of 38\% in the SE and 30\% in submovements. Patient 2 also showed a decrease in both parameters, 25\% in SE and 44\% in submovements.

4. Discussion

The average spontaneous speed in adults is 1.37 m/s in women and 1.43 m/s in men [17]; participant 1 initially walked at a speed of 1.44 m/s, which would normally be acceptable if it was a comfortable speed. However, our participants were asked to walk at the fastest speed possible during the 3MWT. Thus, the increase by more than 0.16m/s in the maximum speed obtained by the participant is clinically relevant as it coincides with the MCID (minimally clinically important difference) referring to acute stroke [18].

In the kinematic parameters, execution speeds remained more or less constant in both participants. That is, an increase in speed does not imply improved kinematics as it could create a lack of control in monopodal support with a rapid collapse of the plegic LE due to gravity. Analytical movement without control does not imply an improvement in the quality of movement, especially in this exercise, in which knee flexion was facilitated by gravity, and a slow eccentric contraction is necessary. The reduction of SE and submovements has positive results and leads to greater precision in performing the task. However, the system software allows to create open and individualized evaluation templates for specific deficits and to evaluate not only the range of motion but also the quality of movement.
of motion but also the accuracy of it. Thus, the decrease of submovements and SE indicates that motor control improved, which carries clinical importance, since an increase in gait speed without this control would imply compensatory mechanisms [19].

With our VR setting, patients didn’t report episodes of discomfort during RFVE treatment and cybersickness (nausea, vomiting, drowsiness, loss of balance, etc.), reported by other authors [20]. Thus, could be an advantage to use a non-immersive system [21]. They were given information about their leg movements during the performance of motor skills (KP) which are necessary for walking, and a “virtual teacher” movement showed the ideal kinematics that the patient’s LE should develop, in order to practice “learning by imitation”. Moreover, the trajectories displayed on-screen allowed patients to evaluate the accuracy of their movement (KR), thereby promoting the identification of successful motor strategies through the “trial and error” paradigm [14].

About the utility of this software, VRRS can be very useful to assess bodily harm, because of the possibility that it brings to evaluate specific movements of the lower limbs, for instance to determine the degree of functional disability of a patient and to compare it with data from healthy subjects. Data storage and analysis is a key factor to link parameters such as speed and spatial error in order to determine not only if the movement can be performed more fastly, but also its degree of precision. It would be very interesting to correlate these data with those obtained by other motion analysis systems used for gait assessment such as Davis protocol. As well, it would be necessary to develop specific sensors for certain important parameters to get a better assessment of the balance and the lower extremity function [22] such as the measurement of the center of pressure during standing. These measures would improve the evaluation of technical aids like exoskeletons to assist patients during motion.

The clinical adaptation of VRRS for LE motor recovery after stroke [23] is a breakthrough, since its possibilities of implementation are increased. The multidisciplinary work of professionals is essential for progress in this field, and an improvement of the computer skills on the part of the therapists is needed [24]. Thus, the detailed description of our intervention could help further understanding of the functional objectives raised.

5. Conclusion

The use of the VRRS software showed its practical utility in enriching physiotherapeutic assessment and treatment in post-stroke gait disorders. The kinematic evaluation offered by the VRRS makes possible to have continuous KP and KR feedback during tasks performance, involving “reinforced learning” mechanism. The clinical application of our VR system, widely demonstrated in the upper limb, shows promising results on their adaptation to LE functional recovery after stroke.

References