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Virtual reality tools for post-stroke balance rehabilitation: a review and a solution proposal

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***Abstract*—Stroke is the leading cause of long-term disability in adults, giving rise to balance loss. Virtual reality (VR)-based tools can complement conventional therapy, accelerating post-stroke balance recovery by evolving the patients in an immersive and enthusiastic environment for balance training. This work aims to review the specifications of VR-based tools regarding the VR technology, embedded sensors, motor tasks, virtual challenges, and control strategies for post-stroke balance rehabilitation and to present a solution proposal to tackle current issues on this topic. This review selected 21 articles from the Scopus database. The results show that screens are the most used VR technology, combined or not with auditory and vibrotactile feedback. Cameras and balance boards/platforms are integrated into VR for real-time feedback of the patients' motion. Treadmill walking, weight shifting/bearing, pelvic/hip movements are the most common motor tasks for balance training. Future research may explore the use of wearable sensors and the user-centered design of closed-loop control strategies and virtual challenges for personalized balance training.**

***Keywords*—balance, rehabilitation robotics, stroke, virtual reality**

I. Introduction

Stroke affects annually 15 million people worldwide, being the leading cause of long-term disability, usually including loss of balance, postural instability, and muscle paralysis [1]. Stroke predominantly affects people over 40 years, compromising their quality of life, professional and social inclusion, and increasing the risk of falling [1].

Post-stroke patients need help from health professionals to regain balance and muscle control through neuroplasticity, so they can independently perform daily tasks [2]. Conventional physical therapies manually commanded by the health professionals can be tiring, aimless, and demanding for many patients, resulting in reduced motivation, compliance with training programs, and causing pressure and/or depression on them [2], [3]. In recent years, robotic technology has developed remarkably, making robotics available for rehabilitation intervention [4]. Robotic rehabilitation tools as virtual reality (VR)-based tools can complement conventional therapy through a user-centered design approach and personalized intensive training that follows users' needs [5], [6]. VR-based tools use the principles of motor learning and neuroplasticity, inducing neural reorganization, which is associated with the restoring of balance functions in stroke patients [7], [8]. VR technology has the advantage of evolving the patients in a multi-sensory, fully immersive, and enthusiast environment for balance training, providing task-specific goals, objective real-time feedback of the performed movements, and promoting intensive individualized repetitive practice [8]–[10]. Thus, increasing the patients' participation and accelerating balance recovery [9].

A review of research development in this topic is essential to accelerate future investigations, considering the advantages and needs that the VR-based tools can bring to post-stroke rehabilitation. Current reviews on this topic, like the ones from Mohammadi et al. [11] and D. Corbetta et al. [12], focus on the clinical effects of VR on post-stroke balance. However, they lack describing the specifications beyond these tools. Thus, there is no review to guide the future design of effective and efficient VR-based tools.

This work aims to review the specifications of VR-based tools for post-stroke balance rehabilitation, such as VR technology, embedded sensors, motor tasks, virtual challenges, and control strategies, advancing current literature reviews [11], [12]. This study advances with a review of all the specifications of VR-based tools for post-stroke balance rehabilitation. It will answer the following research question: What specifications should be considered for the user-centered design of VR-based post-stroke balance rehabilitation? Moreover, it presents a solution proposal of an effective and intuitive VR-based tool for post-stroke balance rehabilitation that holds potentialities and tackles limitations from current solutions to guide future research.

II. Methodology

The studies included in this review were searched in the Scopus database using the following keywords: "measure stroke", "virtual reality", "balance", "rehabilitation", "training", and "recovery". The search type included the "Article title, Abstract, Keywords". Only studies published after 2004 were considered. The reference list of all the relevant found studies was checked. Among the resulting studies, only those

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comprising all the eligibility criteria were included in this review. The inclusion criteria were: (1) use VR equipment; (2) post-stroke patients; (3) aimed to improve balance control; (4) compare VR and conventional rehabilitation. The following specifications of VR-based tools were extracted: VR technology, sensor integration, motor tasks, virtual challenges, and control strategies.

III. RESULTS

After deleting duplicate results and studies that did not meet inclusion criteria, 21 studies were analyzed. The extracted characteristics of the included studies are shown in Table 1.

A. *VR technology*

The VR technology used in the reviewed studies provides visual (21 studies) and/or auditory (15 studies) cues to patients. The study [13] is the only which provides vibrotactile cues through a pager vibrator.

By analysing Table 1, it is possible to visualize three types of display systems (i.e., screen, a combination of screens, head-mounted display [HMD]) commonly used to provide visual feedback to patients in VR-based balance rehabilitation. Sixteen studies provided access to the virtual environment through a television (TV) screen [3], [7], [10], [14]–[17], non-discriminated screen [8], [18]–[20], computer monitor [9], non-discriminated monitor [21]–[23], and video display [24]. Four studies used HMD [13], [25]–[27], one of which discriminated it as being the Virtual Research V6 HMD [13]. Yang et al. [28] proposed a combination of three connected screens.

Eight studies provided auditory cues through TV screen [3], [10], [14], [15], [17], computer monitor [9], and non-discriminated monitor [22], [23], all with built-in speakers. Four studies used external sound devices, such as loudspeakers [8], [18], speakers [24], and three-dimensional (3D) auditory outputs [28]. Three studies used HMD with built-in headphones [13], [26], [27]. The remaining six studies do not report auditory cues [7], [16], [19]–[21], [25].

B. *Sensor integration*

Most studies propose VR-tools with integrated sensors that allow patients to interact with the virtual environment and receive real-time feedback of their movements. Four studies do not mention sensor integration [8], [18], [26], [27].

Eight studies used a camera and half of them with reflective markers. One study utilized two OptiTrack FLEX:C120 cameras (NaturalPoint, OR) belonging to the BioTrak VR system to estimate the 3D position of two markers fixed to the participant's insteps [24]. Three studies used an infrared camera: one from BCT system to measure the four markers' position on the knee [20], and the other two studies used the Kinect sensor (also works as RGB camera) into the Xbox system to monitor the patient's center of mass (COM) (unique position where the sum of the weighted position vectors of all the parts of a system is equal to zero) [15], [23]. Two studies utilized a camera from the IREX system (Vivid group, Toronto, Canada), which determines the markers' position of cyber gloves [7], [16]. Two studies employed a non-discriminated camera [13], [21] that records the leg and foot movements. Jaffe et al. [13] also used flat foot switches to detect collisions.

Six studies used a balance board that measures, in real-time, the patient's center of pressure (COP) (point of application of the ground reaction force vector). Five of the boards belong to the Nintendo Wii Fit [3], [10], [14], [15], [17], [19], and the other is included in the BalPro system (Man&Tel, Gumi, Korea) [19]. This last study also utilized a tilting sensor that estimates the knee joint angle [19]. Lee et al. [20] used two electronic scales included in Balance Control Trainer (BCT) system. In another study, these authors [22] used a platform belonging to the BioRescue system (RM Ingénierie, Rodez, France) to monitor the patient's COP. One study employed the Tetra-ataxiometric posturography (Tetrax) (Sunlight Medical Ltd., Ramat Gan, Israel) that measures postural sway using the change in weight burden onto each of four force plates included in the system [16]. One study used the Stewart platform included in the Rutgers Ankle Rehabilitation System to determine the ankle angle [9]. Yang et al. [28] used an electromagnetic system (Fastrack, Polhemus), which tracks leg motion. Park et al. [25] used a non-discriminated sensor that measures the patient's movement.

C. *Motor tasks*

Looking at Table 1, it is possible to verify that VR-based tools comprise different motor tasks for balance rehabilitation, namely: walking (6 studies), stepping (3 studies), weight shifting/bearing (6 studies), and specific-body movement at pelvic/hip (5 studies: 2 sitting, 2 standing [1 with a harness], and 2 not mentioned), knee (4 studies: 3 standing [2 with and 1 without harness] and 1 not mentioned), feet (4 studies: 2 sitting, 1 standing with a harness, and 1 not mentioned), and trunk (3 studies: 2 standing [1 with a harness], 1 sitting, and 1 not mentioned). Nine studies combined more than one motor task [7], [9], [13], [19]–[23], [25] and four studies did not mention any motor task [3], [10], [14], [17].

Six studies addressed walking, all of them on the treadmill [8], [13], [18], [26]–[28]. Five of them applied different speeds according to the patient's evolution [8], [18], [26]–[28], and only one study varied the slope in conjunction with the virtual environment [28]. Three studies addressed stepping [7], [13], [24]. Six studies addressed weight shifting in the horizontal direction [19], [20], [22], vertical direction [20], [22], and non-discriminated direction [7], [15], [23]. Two studies tackled weight-bearing training [23], [25]. Rajaratnam et al. [15] issued COM change in sitting and standing positions.

Five studies addressed pelvic/hip movement [7], [21], [23], [25], including pelvic tilt in supine and sitting position [25], hip abduction [21], [23], adduction [21], flexion [23], and external-internal rotation [23]. Four studies addressed knee movement [7], [19], [20], [23] focused on knee flexion [19], [20], [23] and extension [20], [23]. Three studies tackled trunk movement [7], [23], [25]. Park et al. [25] mentioned maintenance of trunk stability in supine and standing positions and trunk upright control in sitting position. In another study, these authors exploited trunk rotation [23]. Four studies addressed feet movement [7], [9], [21], [23], tackling dorsiflexion and plantarflexion [9], [21], [23], adduction and abduction [21], and inversion and eversion [9].

TABLE I. CHARACTERISTICS OF THE INCLUDED STUDIES

Study	VR technology	Sensor integration	Motor tasks	Virtual challenges
Barcala et al. (2013) [14]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Plataformas, Pesca Bajo Cero, and Cuerda Floja
Cho et al. (2012) [3]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Balance Bubble, Ski Slalom, Ski Jump, Soccer Heading, Table Tiling, and Penguin Slide
Cho et al. (2013) [8]	Screen and loudspeakers	Not mentioned	Treadmill walking	Walking in a virtual scenario from a real-world video recording
Cho et al. (2014) [18]	Screen and a loudspeaker	Not mentioned	Treadmill walking	Walking in a virtual scenario from a real-world video recording
Huh et al. (2015) [19]	Screen	Balance board and tilting sensor	Horizontal weight shifting and knee flexion	Fruit-Harvesting game
In et al. (2016) [21]	LCD Monitor	Camera	Dorsiflexion and plantarflexion; Adduction and abduction of forefoot and rear foot; Adduction and abduction of the hip	Mimic motor tasks
Kim et al. (2009) [7]	TV Screen	Video-camera and cyber gloves	Weight shifting, stepping, trunk, pelvis, hip, knee, and ankle movement	IREX VR games: Stepping up/down, Sharkbait, and Snowboard
Lee et al. (2012) [20]	Screen	Two electronic scales, an infrared camera, and four infrared markers	Weight shifting in both horizontal and vertical directions, knee flexion, and extension	Board Cleaner game
Lee et al. (2015) [22]	Monitor	Platform included in BioRescue system	Left-right and up-down weight shifting	City Walking, Hot air Balloon, and Bubble games
Lloréns et al. (2015) [24]	Video display and speakers	Two Opti Track FLEX:C120 cameras and two markers	Stepping	Reach virtual items that rose from the ground moving one foot while maintaining the other foot within a virtual circle
Park et al. (2013) [25]	HMD	Sensor that measures the patient's posture and movement.	Trunk stability and pelvic tilting in supine position; Trunk upright control and pelvic tilting in sitting position; Lower extremity muscle strengthening exercise; Weight-bearing	Mimic motor tasks
Park et al. (2017) [23]	Monitor	Kinect sensor (RGB and infrared camera)	Active movement of the upper extremity, weight-shifting, weight-bearing, trunk rotation, active movement of the lower extremity (hip flexion, abduction, and external-internal rotation, knee flexion and extension, ankle dorsiflexion, and plantarflexion)	Xbox Kinect games: Boxing, Table Tennis, Soccer, Golf, Ski, and Football
Rajaratnam et al. (2013) [15]	TV Screen	Balance board and Kinect sensor	Nintendo Wii Fit: weight shifting during standing; Microsoft Kinect: COM change in both sitting and standing positions	Nintendo Wii Fit games
Song et al. (2014) [16]	TV Screen	IREX: camera and red gloves; Tetrax: four force plates	IREX VR: COP movement; Tetrax: not mentioned	IREX VR: five games; Tetrax: not mentioned
Yatar et al. (2015) [10]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Soccer Heading, Ski Slalom, and Balance Bubble
Jaffe et al. (2004) [13]	HMD with built-in headphones and pager vibrator	Video camera and flat foot switches	Walking and stepping	Step over virtual obstacles
Jung et al. (2012) [27]	HMD with built-in headphones	Not mentioned	Treadmill walking	Walking in a virtual park stroll
Kang et al. (2012) [26]	HMD with built-in headphones	Not mentioned	Treadmill walking	Walking in a virtual street
Mirelman et al. (2009) [9]	Computer Monitor	Stewart platform included in the Rutgers Ankle Rehabilitation System	Dorsiflexion, plantar flexion, inversion, and eversion	Navigate a virtual plane or boat towards a series of targets
Morone et al. (2014) [17]	TV Screen	Balance board	Not mentioned	Nintendo Wii Fit games: Hula Hoop, Bubble Blower, and Sky Slalom
Yang et al. (2008) [28]	three connected screens and three-dimensional auditory outputs	Electromagnetic system	Treadmill walking	Walking in a virtual community

Park et al. [25] also addressed lower extremity muscle strengthening exercises and upper extremity active movement. IREX VR system includes five tasks for moving COP [16]. Tetrax system enables left-right and anterior-posterior weight shifting and weight-bearing [16], [29]. Nintendo Wii Fit system, in [3], [10], [14], [17], includes balancing on one leg, leaning, rotating, and moving body to a rhythm [30].

D. Virtual challenges and control strategies

Virtual challenges are intended as tasks taking place in virtual environments controlled to work as serious games.

In [8], [18], post-stroke patients walked on a treadmill while an unsynchronized real-world video recording plays, depicting a sunny or rainy 400-m walking track, a 400-m walking track with obstacles, daytime or nighttime walks in a community, or walking on trails. Similarly, VR-based tools from [27] and [26] simulate a park scroll and street walking, respectively. However, in [26], the optic flow speed is configured according to the 10-m walking test. Yang et al. [28] presented a virtual environment simulating the following scenarios from a typical community in Taipei: lane walking, street crossing, obstacles striding across, and park scroll. The patients are encouraged to uphill and downhill walking (treadmill slope was enabled), fast walking, and step over obstacles while walking on an unsynchronized treadmill. The patients' leg motions were tracked during the obstacles striding across the scenario for providing auditory feedback when detecting collisions with the virtual obstacles. In all the above studies, if the patient was able to walk stably for more than 20 seconds, the treadmill speed was increased by 0.1 km/h, every 20 seconds [26], [27] and 5 % during the subsequent training session [8], [18], [28].

In [13], patients were instructed to step over ten identical stationary virtual obstacles while walking on the treadmill. They received real-time visual feedback of their legs' lateral view and vibrotactile and short sound auditory feedback when a collision with the virtual obstacle occurs (measured when the foot should not be on the ground). The virtual environment from [24] represents the patients' feet with two shoes mimicking their real movement through the positions of the markers placed on each foot. The patients are encouraged to stepping by reaching with one foot the items that rose from the ground while maintaining the other foot within a circle.

Study [21] asked for the patients to observe the real-time movements of the unaffected limb on the monitor and mimic these movements with the affected limb while sitting on a mat without back support. Similarly, in [25], the patients observe in real-time their posture and movement, and they are encouraged to mimic a pre-recorded reference motion.

In [19], the patient's COP and knee flexion are traduced into a horizontal and vertical hand-shaped cursor movement on a screen, respectively. The patients are encouraged to perform weight shifting and knee flexion/extension by moving the screen's cursor to catch fruits (Fruit-Harvesting game). Similarly, in [20], the patients move horizontally and vertically a virtual eraser according to the measurements of electronic scales and position of the markers placed on the knee, respectively. The virtual challenge consists of achieving the maximum score, defined as the percentage of the board cleaned in 2 min (Board Cleaner Game).

In [9], the patients are encouraged to perform ankle movements while sitting to navigate a virtual plane or a boat towards a series of targets according to ankle joint angle.

Lee et al. [22] controlled the virtual environments using patients' COP and encourage patients' weight shifting during the following games: City Walking (left-right shifting), Hot Air Balloon (up-down shifting), and Bubble (total shifting). The IREX VR system, in [7], comprises the following games: Stepping up/down, Sharkbait, and Snowboard, which encourages patients' weight shifting, stepping, trunk, pelvis/hip, knee, and ankle movements. In [16], the IREX VR games are not specified. In both studies, patients are reflected on the screen, interacting with the virtual environment according to the markers' position from the glove and patients' COP. In [16], Tetrax games are also not specified, but according to another study [29], the Tetrax system comprises the following games: Catch, Skyball, Tag, Gotcha, Speedball, Immobilizer, Target, and Freeze, which encourage the patients to move accordingly to the COP.

The Xbox Kinect system, used in [23] and [15], includes the following games: Boxing, Table Tennis, Soccer, Golf, Ski, and Football, which recognize patients' COM. During Boxing, the patients are encouraged to punch virtual objects by moving their arms. In Table Tennis, Soccer, and Golf, the patients must hit a virtual ball with a virtual racket, kick a virtual ball, and put virtual balls in virtual golf holes, respectively. During Ski, the users must avoid the virtual barriers and follow the slope by shifting their weight. In Football game, the patients are encouraged to run with a virtual ball, avoiding the virtual opponent players.

The Nintendo Wii Fit system, in [3], [10], [14], [15], [17], comprises the following games: Soccer Heading, Ski Slalom, Balance Bubble, Hula Hoop, Ski Jump, Table Tiling, and Penguin Slide, which recognize patients' COP. Soccer Heading game encourages the patients to reach virtual balls flying at them and to avoid other flying objects such as cleats and panda heads. In Balance Bubble game, the patients try to avoid virtual obstacles such as walls, rocks, and bees, while going down a virtual river. During Hula Hoop, Penguin Slide, and Table Tilting, the players must catch virtual bows, virtual fish that comes off the water, and to tilt virtual balls into holes, respectively. When performing Ski Slalom and Ski Jump, the patients are encouraged to navigate following virtual flags and to jump off a virtual hill, respectively.

IV. DISCUSSION

This work reviews the VR technology, sensor integration, motor tasks, virtual challenges, and control strategies beyond VR-based tools to guide future research on user-centered design of VR-based post-stroke balance rehabilitation.

A. What specifications should be considered for the user-centered design of VR-based post-stroke balance rehabilitation?

Most of the reviewed studies used a single screen. This preference can be explained once a screen is generally a cost-effective solution for a VR-based tool when compared to multiple screens and even more an HMD. Moreover, in opposition to an HMD, the screen allows the physiotherapists to follow in real-time the patients' performance during the balance training and, consequently, efficiently provide additional support to patients [31]. However, the combination of screens and HMD provides greater immersion in the virtual environment than the screens. The full immersion in the virtual environment promotes patients' concentration, involvement, and active participation in balance training, leading to an efficient recovery [32]. Furthermore, in opposition to the screens, the HMD is a wearable setup device. Moreover, some studies described the use of auditory (mainly) [3], [9], [10], [14], [15], [17], [22], [23] and vibrotactile cues [13], filling the gap of auditory and haptic interaction, respectively, with the virtual environment.

Most of the VR-based tools include sensors to provide real-time feedback of patients' movements and to allow the patients to effectively interact with the virtual environment. Those who did not mention the use of sensors [8], [18], [26], [27] only use VR technology to develop unsynchronized virtual environments. Most of the reviewed studies used a camera or a balance board/platform as sensors. They have a promising impact in balance training once they provide an objective assessment of patients' position, posture, COM, and movement in the case of a camera and patients' COP in the case of a balance board/platform. However, both cameras and balance boards/platforms are non-wearable, limiting the VR tools to clinical practice to an indoor fixed facility.

VR-based tools were exploited to guide the execution of different motor tasks, including walking, stepping, weight shifting/bearing, pelvic/hip, knee, feet, and trunk movement. Treadmill walking, weight shifting/bearing, and pelvic/hip movement are the most encouraging motor tasks, highlighting the role of both upper and lower limbs in balance control. Some studies [7], [9], [13], [19]–[23], [25] combined at least two motor tasks, enabling a more holistic balance training, personalized according to the patients' imminent needs and indispensable for an independent daily living [33].

Treadmill walking was mainly addressed alone in opposition to the remaining motor tasks. Moreover, the VR-based tools that encourage treadmill walking use sensors only to develop a virtual environment. Thus, there is space to develop VR-based tools combining walking with other motor tasks and integrating sensors to provide real-time feedback and allow patients' interaction with the virtual environment.

Most of the VR-based tools comprise a closed-loop control, providing real-time feedback according to integrated sensors' objective measures. Feedback encourages the patients to self-control their movements towards motor relearning [34]. The virtual challenges applied in closed-loop VR-based tools have no trend but are dependent on the encouraged motor task. These challenges imply the development of serious games generally aiming to catch, avoid, or navigate virtual objects, fostering patients' enthusiasm and motivation. Thus, patients are encouraged to perform implicit motor tasks to accomplish the virtual challenge, improving their balance control. Although the variety of VR-based tools found in the literature, none suggests a user-centered design, once virtual challenges were not tailored to the actual user's motor needs, which can limit the clinical outcomes. Therefore, there is space in future research to compare the efficacy of post-stroke balance rehabilitation of VR-based tools specifically designed for this purpose with existing VR-based tools.

B. Solution proposal: VR-based tool for post-stroke balance rehabilitation

Future design of a VR-based tool for post-stroke balance rehabilitation may include the simultaneous use of screens and HMD to provide full immersion for patients and to allow efficient participation of physiotherapists towards a more cost-effective solution, advancing reviewed studies. Vibrotactile and auditory feedback may also be explored to augment sensory interaction with the virtual environment, as in [13]. Wearable sensors may be innovatively integrated into these tools once they can be more cost-effective solutions while ensuring accurate motion tracking in multiple scenarios. Moreover, they provide real-time feedback and allow the patient's interaction with virtual environment. Closed-loop control strategies and virtual challenges may be developed following a user-centered design, as demanded in the literature. Thus, through a serious progressive game, the patients are encouraged to perform a combination of motor tasks oriented to their actual motor needs and according to their motor evolution, including walking.

V. Conclusion

This review focuses on the specifications of VR-based tools for post-stroke balance rehabilitation. Screens are the most used VR technology, cameras and balance boards/platforms are the most used sensors, and treadmill walking, weight shifting/bearing, and pelvic/hip movements are the most performed motor tasks. Closed-loop control strategies are mainly developed, providing real-time feedback of patients' movement and COP. Catching, avoiding, and navigating virtual objects are the generally referred virtual challenges that patients are encouraged to perform aiming at balance training. Future work may include the use of integrated wearable sensors and the user-centered design of closed-loop control strategies and virtual challenges for personalized balance training.

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