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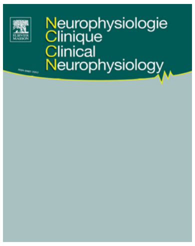

REVIEW/MISE AU POINT

Advantages and limitations of virtual reality for balance assessment and rehabilitation

Avantages et limites de la réalité virtuelle pour l'évaluation et la rééducation de l'équilibre

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Summary Virtual reality (VR) is now commonly used in many domains because of its ability to provide a standardized, reproducible and controllable environment. In balance assessment, it can be used to control stimuli presented to patients and thus accurately evaluate their progression or compare them to different populations in standardized situations. In balance rehabilitation, VR allows the creation of new generation tools and at the same time the means to assess the efficiency of each parameter of these tools in order to optimize them. Moreover, with the development of low-cost devices, this rehabilitation can be continued at home, making access to these tools much easier, in addition to their entertaining and thus motivating properties. Nevertheless, and even more with low-cost systems, VR has limits that can alter the results of the studies that use it: the latency of the system (the delay cumulated on each step of the process from data acquisition on the patients to multimodal outputs); and distance perception, which tends to be underestimated in VR. After having described why VR is an essential tool for balance assessment and rehabilitation and illustrated this statement with a case study, this review discusses the previous works in the domain with regards to the technological limits of VR.

MOTS CLÉS
Réalité virtuelle ;

Résumé La réalité virtuelle (RV) est utilisée dans de nombreux domaines puisqu'elle permet d'avoir un environnement standardisé, reproductible et contrôlable. Pour l'évaluation de l'équilibre, elle permet de contrôler les stimuli visuels proposés aux patients et donc d'évaluer précisément leur évolution ou de les comparer à d'autres populations dans un environnement

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Équilibre ;
Évaluation ;
Rééducation

standardisé. Pour la rééducation de l'équilibre, la RV permet la création d'une nouvelle génération d'outils et en même temps le moyen d'évaluer chacun des paramètres de ces outils pour les optimiser. De plus, avec le développement des dispositifs bas coût, la rééducation peut se poursuivre à domicile, rendant les outils plus accessibles, en plus de leur aspect ludique et donc motivant. Néanmoins, et particulièrement avec les systèmes bas coût, la RV possède des limites qui peuvent altérer les résultats des études qui l'utilisent : la latence du système (le délai cumulé par toutes les étapes du processus allant de l'acquisition des données des patients jusqu'au rendu multimodal) et la perception des distances qui est sous-estimée en RV. Après avoir décrit les raisons pour lesquelles la RV est un outil essentiel pour l'évaluation et la rééducation de l'équilibre et l'avoir illustré avec un cas d'étude, cette revue fait la correspondance entre les études de la littérature dans ce domaine et les limites technologiques de la RV.

Introduction

Virtual reality (VR) is now commonly used in many domains, such as for the training of aircraft pilots or workers ensuring the maintenance of nuclear sites, both for security and economic reasons. Similarly, in the medical field, VR has been used for instance in the training of surgeons, especially for laparoscopic surgery [60]. The environment provided by VR is not only safe but also standardized and controlled. For example, the treatment of anxieties and phobias [45,47] with VR has the advantage that the stimuli presented can be controlled, so that patients can face their fear gradually. VR also allows analyses and experiments that cannot be performed in real situations, for example by moving the surrounding world. For all these reasons, clinicians have studied for many years the potential advantages of incorporating VR technologies into the assessment and rehabilitation of patient training. Some companies even propose off-the-shelf solutions such as CAREN (Motek Medical, Amsterdam) or IREX (GestureTek, Toronto).

Recently, the video game industry has strongly progressed in the creation of low-cost systems such as Microsoft Kinect (Microsoft Corp., Redmond, Washington) or Nintendo Wii (Nintendo Co. Ltd., Kyoto, Japan). This has facilitated the creation of a series of games for training and rehabilitation: the so-called ''exergames'' [52]. Levac et al. even proposed resources to support decision-making about integration of Kinect into rehabilitation practice [34]. The emergence of crowd-funded products, such as Oculus Rift or Razor Hydra, all financed by the Kickstarter company, is also accelerating the use of VR for rehabilitation, even at home [53].

Thus VR seems to be a promising tool for clinical assessment and rehabilitation because of its many advantages: standardization, reproducibility and stimuli control. Nevertheless, as a digital tool, it is based on software computations and hardware devices. Perception and interaction of the patient with this virtual environment can thus be altered and can lead to wrong analyses. Several reviews have been published dealing with the use of VR for balance rehabilitation, especially after stroke [8,14,35]. The goal of this review is to address the problem from a technological point of view, to describe the studies that have made use of VR for balance assessment and rehabilitation, focusing on the advantages and especially the limits of VR that are sometimes omitted or understated.

The selected papers were therefore chosen if they deal with the use of VR either for balance assessment or rehabilitation (searched on PubMed, ScienceDirect and Google Scholar). Firstly, returned hits were filtered according to the accuracy of the description of their VR setup whether they provided information about outcomes. They were then selected depending on the technology used. For example studies in which the VR was just considered as a distractor (exergames on mobile phones for instance) or just a screen with no interaction were not kept. Finally, abstracts and non-English papers were excluded from this review.

This paper is composed of a case study to exhibit the advantages and limitations of VR for balance assessment and rehabilitation, with the literature review on these two topics presented thereafter.

Why virtual reality for balance assessment and rehabilitation?

Case study of pendulums for balance assessment

Many protocols can be setup to evaluate the balance recovery of patients. As soon as imbalance is induced, the process of how the patient returns to equilibrium can be studied. Nevertheless, it is necessary to have a standardized and reproducible environment to compare the trials of patients (evolution of their balance through time, training sessions, etc.) or to make comparisons between patients. Video provides such a standardized environment but in several domains, VR has exhibited better performance than video e.g. laparoscopic surgery [21] or physical activity [6], certainly due to its ability to propose an adaptive viewpoint and a stereoscopic vision. In the present paper, we ask the following question: Could VR be just as pertinent for balance assessment and rehabilitation?

Consider the training of balance recovery for elderly people with the use of a system composed of three pendulums. The objective of such a system is to slowly throw balls toward the head of the patient, forcing him to move in order to avoid collision and then to recover balance. The three

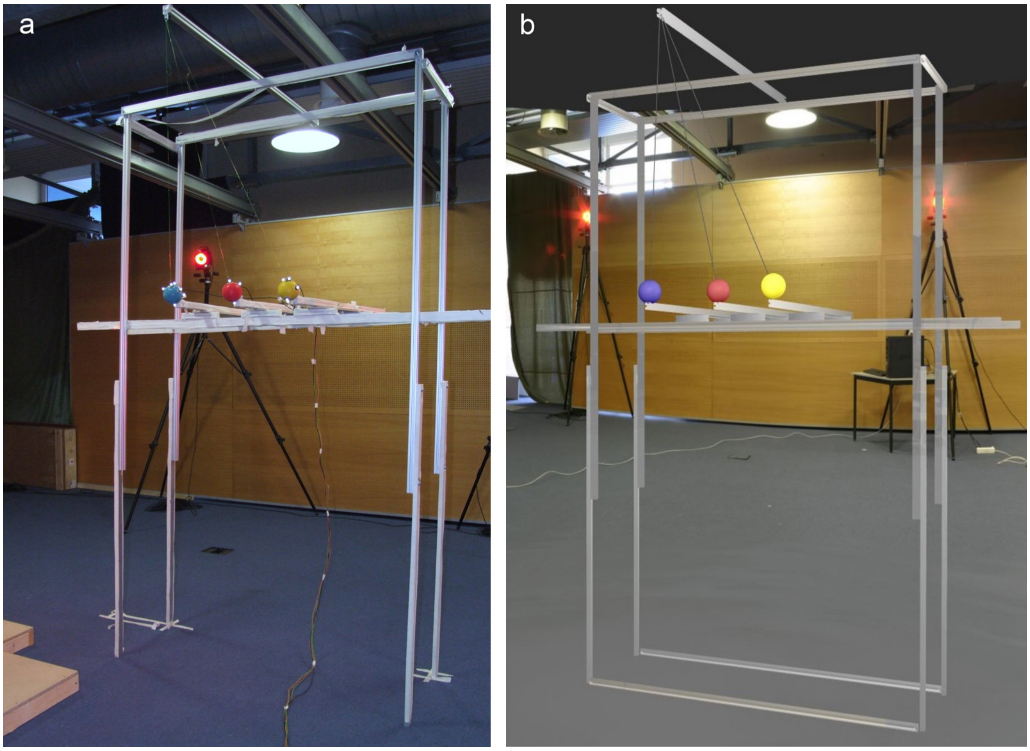

Figure 1 Case study setup: a: a real structure composed of three pendulums. It can be manually adjusted to the patient's height and to control the orientation and speed of the balls; b: the same structure in a virtual environment. It can be automatically adjusted for the patient's height and to simulation parameters.

balls ensure uncertainty from where the ball is coming to avoid anticipation.

This system can only be usable if two main issues are solved. First, it must be adapted for the different morphologies of patients. The balls must indeed go toward the head whatever the size of the patient. Second, the speed of the balls must be controlled since it depends on the ability of the patient to quickly avoid the ball or not. This aspect could be related to the age or the physical fitness of the patient for instance.

The first solution is to create a real structure in which the wires of the pendulum must be adaptable to control the trajectory of the balls (see Fig. 1a). This can be achieved by adjusting:

- the height of the spire to which the wires are tied, to deal with the patient's morphology;
- the starting position of the balls and the length of the wires to change the speed of the balls.

Besides the cost of conception and development of such a system, two main problems arise. The space needed to install this structure is often incompatible with a doctor's office but more problematic is the parameterization of the system. For instance, to modify the height of the structure, it is necessary to unscrew, move and re-screw the metallic bars. Further complexity determines the configuration of the structure, since the height of the spire also depends on the length of the wires that depends on the desired speed of the balls, which also depends on the starting position of the balls. This kind of system is therefore not suitable for the training of several patients.

The second solution is to create a virtual representation of this structure and to use VR to control its simulation and immerse the patient in front of it (see Fig. 1b). Several steps are then required:

- creation of the virtual environment;
- creation of the kinematic simulation of the pendulums;
- setup of the inputs (head tracking and force plate) and output (visual feedback).

In this virtual environment, the simulation of the balls can be computed with automatic adaptation of the entire structure from high-level parameters such as the patient's height.

With the emergence of new low-cost devices, this kind of system can be used in a doctor's surgery, for example by combining a Microsoft Kinect to capture the motion of the patient and an Oculus Rift to immerse the subject into the virtual environment with stereoscopic vision and embedded head tracking, allowing a 360 degree field of view. Finally, a Nintendo Wii Balance Board can be used to acquire the center of pressure displacement.

This case study thus shows how VR can provide a standardized, reproducible and controllable environment that allows the analysis and rehabilitation of balance. Nevertheless, the same way it reveals strong advantages, it has some limitations that can alter the results obtained with such a system.

Advantages and limitations of VR

Many studies based on VR, range from experiments with 3D projection of objects on a monoscopic screen up to the immersion of the subject with multi-sensory feedbacks (visual, tactile, and auditory for example). Such a large disparity in studies is explained because there is not a single definition of VR. The most common definition is that VR is a scientific and technical domain that exploits computer sciences and behavioral interfaces. More precisely, VR consists of simulating the behavior of 3D entities that interact with each other in real time and with users, immersed in a pseudo-natural manner through sensorimotor channels. A VR system is efficient when the user has the ''feeling of being there'' (in the virtual world) [49,51], which is the concept of presence [24]. According to this definition of VR, some papers on balance assessment and rehabilitation do not really use virtual reality since there is no interaction but only a means of disturbing the vision of the patient; these articles were not selected for this review.

As stated above, the first advantage of VR is the complete control of the stimuli provided to the subject, being the main reason to use VR because it provides a standardized and reproducible environment [55]. The second advantage is the ability to have stereoscopic vision that gives the subject salient motion-in-depth information [50]. Moreover, the viewpoint of a virtual environment can be adapted in real time to correspond to the subject's one. Finally, in addition to these advantages, VR is often seen as a fun training tool increasing the motivation of patients to continue their rehabilitation.

Nevertheless, all these advantages are obtained thanks to software computations and hardware devices. All the steps from the capture of information (motion, center of pressure, etc.) to the multi-sensory feedback (at least visual) take time; this delay can be perceived by the immersed patient and can modify his reactions. This is called the latency of the system. The second main limitation of VR is different distance perception [48]. The latter is indeed underestimated in VR compared to a real situation. Depending on the type of study, it is thus necessary to take into account these limits that are often ignored or understated. They can indeed alter patients' actions with for instance different amplitude of center of pressure or reaction times in VR compared to real situations.

Evaluation of the case study between real and virtual environments

To consider the relevance of using VR for balance assessment or rehabilitation, we performed an experiment based on the case study described above with the three pendulums. The objective was to compare the reaction of the subject in reality and in VR during balance recovery, as it has been done for example in sports where the reactions of a goalkeeper in front of a real kicker were compared to the same situation in VR in front of the virtual kicker [5]. Nevertheless, in such a study, only the kinematics of the subject is analyzed. When dealing with balance assessment and rehabilitation, studying the motion dynamics is essential.

The experiment proposed in the following three conditions:

- in the reference condition (real) the subject is placed in front of the real structure and has to avoid the balls (see Fig. 1a);
- the second condition evaluates the influence of having a head-mounted display (HMD) device only. The HMD can indeed influence the motion dynamics of the subject by weight or by altering the way he moves, for instance due to the wire connecting the HMD to the computer. We thus used a special see-through HMD, which can be used as glasses if no images are projected (Visette 45 SXGA, Cybermind, dedicated to virtual and augmented reality);
- the last condition (VR) is the immersion of the subject in the VR environment presented in Fig. 1b using the HMD without the see-through option.

In these three conditions, 18 healthy subjects had to simply avoid the incoming balls that are thrown one at a time in a randomized order to avoid anticipation, real balls for the two first conditions and virtual balls for the third one. Each trial is repeated 10 times. Data collected were the center of pressure (CoP) displacement and the ground reaction forces (GRF).

As described in Fig. 2a, the results first showed that the response time of the subject was significantly delayed in VR compared to the two real situations (with or without HMD). A delay can indeed be observed in the first variation of CoP and the evolution of ground reaction forces. It is quite constant since its value is 270 ± 5 ms.

Concerning the amplitude of the reaction, Fig. 2b shows that the subject's behavior is similar; the Anticipatory Postural Adjustment is preserved in VR but with a small increase of amplitude compared to real situations. As illustrated in Fig. 3, the peak values of the ground reaction force and CoP mediolateral displacement are significantly greater in VR than in the other two conditions.

The first of the two main findings from this experiment was that there is no significant difference between the two situations in reality, with or without HMD. Wearing this HMD device does not disrupt the subjects in a way that causes them to modify their performance. Secondly, although the subject's behavior is similar in real situations and in VR, the reaction of the subject in VR is overstated and delayed compared to real situations. This delay is quite constant and may be mainly due to the latency of the system, since the underestimation of distance perception in VR would have led the subjects to consider that they have less time to react than in reality and the results are in contradiction with this statement.

A see-through HMD device was chosen for this experiment because it ensures that the only difference between the HMD and VR conditions is the visual display of the virtual environment. Nevertheless, we can consider that these results can be dependent on this model of HMD. The results must then be observed as qualitative and not quantitative.

Finally, there was no haptic feedback to inform the subject whether the virtual ball has touched him or not. One can consider that the subjects would react less since they are not afraid of the collision. The results are in contradiction with this statement.

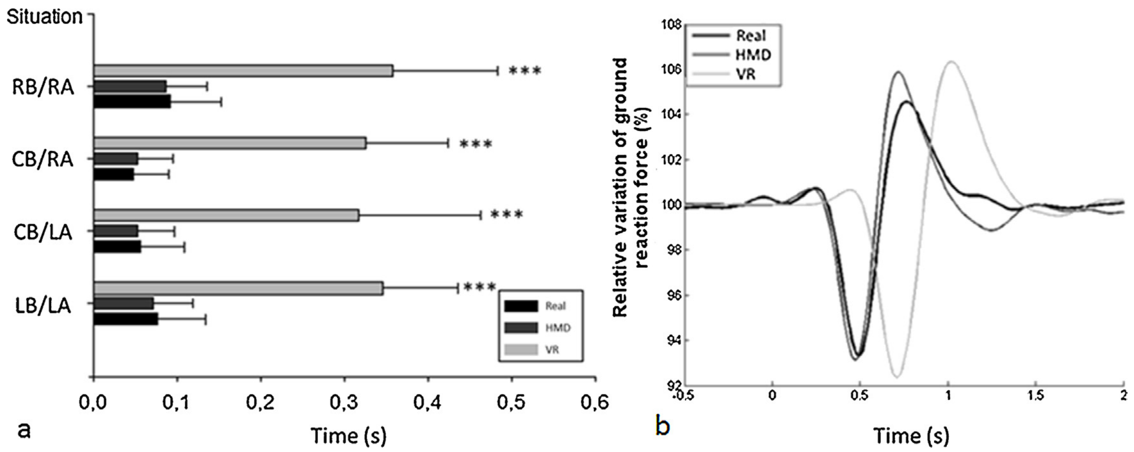

Figure 2 a: time of first variation of the center of pressure (CoP) for the 4 conditions: right ball released with right side avoidance (RB/RA), centered ball released with right side avoidance (CB/RA) and with left side avoidance (CD/LA) and left ball released with left side avoidance (LB/LA); b: norm of ground reaction forces, expressed in percentage of body weight.

This experiment emphasizes the advantages of VR for balance assessment. Indeed, even with such a simple study, setting up the experiment is actually very complex due to the variability of morphologies and abilities of the patients. It thus shows the strength of VR: a standardized and reproducible environment that can be simply adjusted with high-level parameters. This experiment also emphasizes the importance of considering the limits of VR for balance assessment. Before reviewing the papers that worked on balance assessment and rehabilitation, let us first consider works that have evaluated VR for that purpose.

Evaluation of VR for balance assessment and rehabilitation

Without any external perturbation, Horlings et al. [25] compared the stability of patients between real and virtual situations in quiet stance. Seventeen young subjects performed four tasks (standing with feet close together or tandem stance on firm and foam surfaces for 60 seconds under three visual conditions: eyes closed, eyes open without VR, or while viewing a virtual reality scene which moved with body movements). Their results showed that VR causes an increase in postural sway in amplitude similar to that caused by closing the eyes. This increased sway was present irrespective of stance surface, but was greatest on foam. This work tends to demonstrate that stability is not similar between real and virtual environments. Contrary to the case study presented above, the experimental conditions were not the same in both environments, since the subject did not wear any HMD in the real situation. Nevertheless, the HMD device was a light one, and can thus explain that the results were similar, showing a larger movement in VR than in reality. However, in these two studies, the small field of view of the HMD devices (28° in this study and 36° in the case study) has certainly changed the peripheral vision of the patient, this being very important in balance stability [22,46]. Thus it could be interesting to carry out the same study with a new generation of HMD. Chiarovano et al. [10] indeed performed such a study on 27 subjects equipped with Oculus Rift DK2 and compared the balance of the subjects on Wii Balance Board (with or without foam) with the gold standard Equitest (Neurocom, Clackamas, OR, USA), with eyes closed or open; the results showed no significant difference.

Similar works have been completed for rehabilitation, where Meldrum et al. compared the relative effectiveness of conventional and virtual reality-based vestibular rehabilitations [39,41]. The VR-based training protocol was based on Nintendo Wii Fit Plus, which showed high levels of usability and enjoyment with no serious adverse effects [40]. The results showed that virtual reality systems are more effective than conventional rehabilitation of unilateral peripheral vestibular loss [39]. Nevertheless, in another

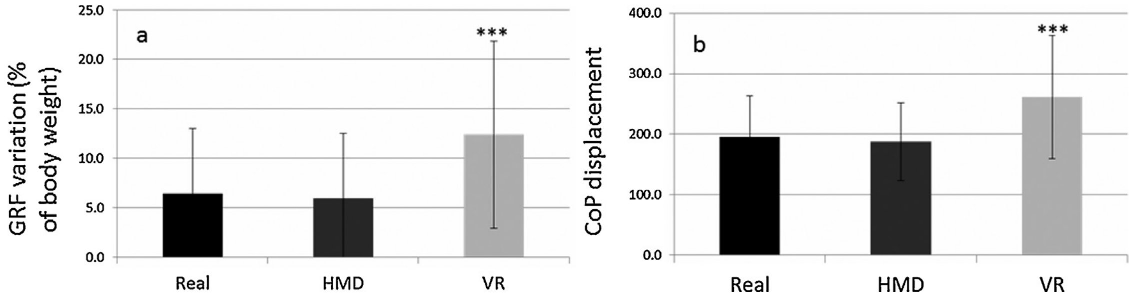

Figure 3 Mean variations for GRF and CoP mediolateral displacement for all situations. *** stand for significant statistical differences ($P < 0.001$).

paper, the same authors concluded that both protocols improve subjects' performances without any significant difference between them, except in terms of pleasure that subjects had following the VR-based rehabilitation [41]. Thus VR can sometimes be more efficient than conventional rehabilitation methods but it strongly depends on the pathology of the patients. Nevertheless, it seems to allow at least an efficient rehabilitation comparable to classical methods.

Cikaljo et al. [13] have evaluated the use of VR for balance telerehabilitation and drew the same conclusion. Patients with stroke performed balance training over a 3-week period, 2 weeks in the clinical settings and 1 week in the home environment, five times a week, and each time for up to 20 minutes. The results showed that the telerehabilitation approach in VR improved balance in stroke patients and had similar effect on patients' postural functional improvement compared to conventional balance training in clinical settings.

Only a few studies have evaluated VR for balance rehabilitation but they converge on the fact that it provides similar progress while adding motivation with an entertaining training tool. Nevertheless, the results are less positive for balance assessment. The patients immersed in VR indeed made larger displacements than in reality, which is problematic if the comparison with real data is done but can still be useful when comparing the patients in the same condition (all in VR). The impact of VR thus depends on the type of study. Let us first consider the studies on VR for balance assessment and then those on VR for balance rehabilitation.

VR for balance assessment

As illustrated in the case study presented above, assessing balance can be carried out using VR because of its complete control of the stimuli presented to the patients, amongst which vision is the easiest to control. Several authors have thus proposed modification of the visual information displayed to evaluate their influence on posture control. Several authors have for instance used visual controlled stimuli such as a 3D tunnel with different properties (size, frequential or linear movements, etc.). Piponnier et al. worked on the importance of visual and peripheral visions on posture control [46]. Their work consisted of 19 healthy young adults immersed in front of a 3D tunnel, which was either static or moving sinusoidally in the anterior—posterior direction. Nine visual field conditions were proposed: four central conditions (4, 7, 15, and 30°); four peripheral conditions with central occlusions of 4, 7, 15, and 30°, and a full visual field condition. The results showed that, in a static environment, the contribution of the visual system in postural control is invariant, regardless of the part of the visual field stimulated. Contrarily, when linear motion appears in the optic flow, the results suggested that peripheral vision plays a greater role on postural control. Greffou et al. made similar experiment with the same virtual environment to evaluate the influence of the frequency of oscillation of the tunnel on balance depending on the age of the patients [19,20]. The results showed that children younger than 16 years old rely mainly on vision to control their posture. Balance stabilization occurs between 16 and 19 years, and remains stable in adult life thereafter before decreasing after 65 years. In the same way, Lee et al. assessed the balance of children (7—10 years) with a HMD and 6 visual stimuli of a tilting virtual environment [33]. The results showed that their capacity of sensory organization is indeed different from that of young adults but the reliability of their system is based on a qualitative comparison with the literature.

Eikema et al. also studied the influence of age on the postural control but regarding the modulation of sensory reweighting [15]. Young and elderly patients stood on a force plate under two conditions: quiet standing and standing while anticipating randomly approaching virtual objects to be avoided. The visual surrounding was removed or degraded every 60 s to evoke sensory re-weighting processes. The results showed that in quiet standing, elderly patients had greater sway variability and were more severely affected by the removal or degradation of visual surround information. Nevertheless, during visual anticipation, the sway variability was not different between the age groups and they were similarly affected by the degradation or removal of the visual surround. These results are in accordance with the works above since the mean age of the elderly population was 71.5 years.

To study the influence of vision on balance control in VR, some authors proposed determining the visual stimuli that cause most disturbance to balance. Tossavainen et al. immersed 22 patients in virtual environments using HMD devices and measured their sway with a force plate [56]. The baseline values were acquired without stimulation in three configurations: eyes open, eyes closed and wearing a HMD without stimulus. Three virtual environments were displayed: a 3D oscillating tunnel, a rotating cylinder, and oscillating and rotating dots. The results showed that the 3D tunnel was the most destabilizing stimulus while the cylinder was more effective on some patients. They open interesting perspectives since different virtual environments could thus be proposed to differentiate pathological responses from normal ones, and perhaps quantify the degree of pathology.

Since VR allows the complete control of the stimuli presented to the patients, several authors proposed going further, by studying sensory conflicts in order to evaluate balance assessment. Following the work of Akiduki et al. [2], Nishiike et al. examined the visual-vestibulosomatosensory conflict induced by different sensory inputs on postural stability [44]. Two different VR conditions were presented. In the control condition, subjects walked in a virtual environment composed of background images that moved synchronously to their walking pace. In the conflict condition, the background images were moving but the subjects stood still. The results suggested that the conflict condition induced motion sickness, resulting in postural instability. They also suggested that adaptation to the conflict condition decreases the contribution of visual inputs to postural control with re-weighting of vestibulosomatosensory inputs. Being able to control the different stimuli makes VR a convenient tool to study sensory conflicts by inducing sensory re-weighting of postural control. Nevertheless, sickness experienced by the patients can also be accentuated by the latency that is a component of the stimuli proposed, and cannot then be ignored.

Still with regards to sensory conflict, Keshner at al. also studied this during a stabilization task [28]. In this experiment, healthy adults and adults with bilateral labyrinthine deficiency were standing on a support surface that was constantly translating with a 0.25 Hz sinusoid. On the contrary, the displacement of the visual environment was varied in direction and frequency. To evaluate postural stabilization, a kinematical analysis of patients' posture was performed. Their results confirmed that visual input is an important component of stabilization. More interestingly, they also exhibited that the reaction to the amplitude of virtual environment displacement was related to the availability of vestibular information. The authors concluded that VR could support both diagnosis and rehabilitative training of individuals with sensory integration impairments. Keshner et al. also used VR to assess the ability of healthy adults and adults with labyrinthine deficit to react to a loss of balance [29]. To this end, they proposed three input configurations: the force plate supporting the patient is translated, or the virtual world is moved, or both are translated. The results showed that when there is a confluence of meaningful inputs, none of the inputs are suppressed in healthy adults; the postural response is modulated by all existing sensory signals in a non-additive fashion. Labyrinthine deficient adults suppress visual inputs.

Bugnariu et al. also studied conflicting visual and somatosensory stimuli on young and old adults [9]. They analyzed concurrently the center of pressure (CoP), the center of mass and the muscular activity thanks to an EMG system. Four perturbations were proposed: visual-only and surface-only (in which only the virtual environment or the supporting surface was tilted), and concordant and discordant (visual and surface perturbations moved synchronously in the same or opposite direction). The results showed that the visual-only perturbation elicited minimal postural responses compared to others, suggesting that the information is weighted more in regulating upright posture. Nevertheless, as in the study of Greffou et al. [19,20], aging influences stance recovery, especially in the presence of sensory conflicts.

After having assessed their system by comparison with the gold standard Equitest, Chiavorano et al. proposed to determine the influence of visual input on the balance of patients with or without vestibular handicap [10]. Thus they compared the balance of patients equipped with Oculus Rift; balance was measured using a Wii Balance Board either covered with foam or not. Several conditions were analyzed: eyes open or eyes closed, in front of a virtual environment that was fixed, rotating/translating or composed of disturbing moving dots. The results first showed that the movement of the virtual environment made the patients fall when its motion speed was above a critical threshold. This result was nevertheless subject-dependent. Second, they highlighted that the fall correlated to the direction of the disturbing dots.

All these works illustrate that VR provides an infinite number of configurations, combining visual and/or haptic inputs that can be used for balance assessment. For each of these inputs, the stimuli can be widely varied but are always controllable and reproducible. For visual input for example, the stimulus could be a 3D tunnel, dots or realistic environment. The design of balance assessment tools is then not limited by technology and only requires finding the best stimuli in accordance to the pathology of the studied population. Nevertheless, there is still a lot of work that must be done to better understand what kind of visual stimuli is the most pertinent for each pathology, or whether some stimuli might be ''generic''.

Concerning the limits of VR, these works have confirmed the predominance of visual input and the importance of taking into account the presence of conflict between the senses. Thus it is important to minimize the latency as much as possible since it can even modify the computation of sensory re-weighting. Nevertheless, all these studies used the same input stimuli for the patients and the comparison was made between groups of people, making latency as less a problem since its influence was the same for everyone. This limit is then decreased by the ability of VR to control all the stimuli and to propose a reproducible environment. However, if the latency is not constant due to processes that are started on the computer during experimentation or due to the variation of network performance for instance, then this must be taken into account even when the comparison is made intra-individually. Concerning distance perception, no work has so far dealt with this, in contrast to other domains such as locomotion assessment [17,27]. The distance of the virtual environment used for balance assessment or rehabilitation is often small so it has less influence on the perception in VR, but it would be interesting to validate this statement.

VR for balance rehabilitation

The advantages of VR highlighted before on balance assessment can be used as a training tool for balance rehabilitation. VR is based on a large number of software and hardware technologies. The choice of these technologies has an influence on the degree of immersion and presence of the patients and thus the potential effectiveness of the system on their rehabilitation. Furthermore, this choice has also consequences on the information perceived. For instance, the depth information cannot be well perceived without stereoscopic vision and not all the visual information can be picked up without being able to change the subject's viewpoint such as with a head tracking system. These devices can thus modify the distance perception as discussed above. In this section, we review the papers according to their technological choices.

The easiest display that can be used in a VR system is a flat screen without any stereoscopic vision. Many studies have used such a system in balance rehabilitation, adding an input device that allows the patient to control a virtual environment by weight shifting, rotation or inclination of his body. The first input device used is a force platform or a balance board. It records the center of pressure and potentially the force applied on the board and transforms those data as an input for the movement in the virtual environment.

Based on such a system, several authors worked on weight shifting of patients, elderly people or persons with pathology such as Parkinson, either on a balance board [18,32,37,57] or on an inclinable force platform [59]. Yen et al. used the CoP of the patient to shift a virtual character in a classical environment or to incline a virtual plate containing balls that roll until they fall in a hole [59]. After several weeks of training, comparison is made between the improvement of a control group and the VR group to quantify the added value of VR. They concluded that both training groups were equivalent; only the prevention of risk of falls was be more effective in sensory and visual reduced conditions with VR. In the same way, Gomez et al. and Kosse et al. provided homemade games (for instance a maze inside which balls are moving) whose difficulty can be adjusted depending on the subjects' level [18,32]. The performance of the subjects was measured with Berg Balance Scale (BBS), Brunel Balance Assessment (BBA) and figure of eight before and after the therapy, pointing demonstrating subjects' improvement in terms of balance and motivation. Nevertheless, they showed that even if patients made progress in static tests, only improvement in dynamic tests was significant. Although, Gomez et al. had significant differences on static tests and not dynamic ones, their system was optimized for static tests, which helps to explain this difference of results.

Lloréns et al. also proposed two studies based on weight shifting [37]. The first one was similar to the study by Jones et al. [27] and proposed games involving displacements of the CoP in the mediolateral plane, in the mediolateral and anteroposterior axes and with free displacements. The second one included one-leg standing, stair climbing, one foot rising and sit-to-stand transfer. The results of these two studies showed that the patients were better than the control group in static conditions (especially in standing position) while their progress in dynamic tests was not significant, in agreement with the results of Kosse et al. [32]. The authors suggested that these results were due to the choice of the exercises that mainly promote the recovery of static balance. The fact that several games turned out to be more effective than others demonstrates the relevance of VR for rehabilitation but also highlights the importance of the selected game for rehabilitation.

Mendes et al., Agmon et al., and Cho et al. did not create a specific virtual environment but selected some of those available in the Wii Fit device, requiring multidirectional shifts, alternating steps or stationary control of the player's center of mass and trained the subjects for several weeks [1,11,42]. The evaluation of the improvement was done either with the reach test (maximum distance a subject can reach without moving his feet from the floor) or with different classical parameters (BBS, BBA, Stepping Test [ST], etc.). The objective was to quantify the loss of balance for patients with Parkinson's disease or Acquired Brain Injury (ABI) in elderly subjects and to find a pertinent means of their rehabilitation. Mendes et al. showed that out of the 10 games presented to their subjects, patients with Parkinson's disease showed no deficit in learning or retention in 7 of them. The 3 other games were associated with high cognitive demands. Nevertheless, patients with Parkinson's disease were able to transfer motor ability trained on the games to a similar untrained task but 2 out of the 3 games where they did not progress involved stationary gait. On the contrary, Cho et al. found greater improvement on dynamic balance tests in the VR group than in the control group and no significant static improvement (in anteroposterior and mediolateral postural sway). Using another set of games, Agmon et al. proved the efficiency of VR through the improvement of BBS and walking speed of the subjects. Beyond this quantitative result, the improvements of the participants obtained during the games seem to have been maintained in their everyday life. The authors also described that enjoyment and discouragement differed for the games and must then be taken into account in the choice of the right game for the right patient.

Another way to exploit weight shifting is to use specialized devices equipped with sensors. For example, Cikaljo et al. placed stroke subjects [12] in an apparatus made of aluminum and wood, preventing the subject from falling and enabling him to move a virtual character by weight shifting. The character must travel across a path full of obstacles as fast as possible; modifying the number of obstacles can change the level. These authors quantified the evolution of the subject with BBS before and after the therapy and by considering the travel time of the virtual character. After training, BBS and Timed-Up-and-Go (TUG) tests provided significant improvements and patients performed the task quicker and with fewer collisions. Jeong et al. also created a specific object to develop balance rehabilitation of stroke subjects in 3 conditions: without any feedback, with feedback of their weight shifting or of their CoP in real time. The patient has to travel across a virtual road on a bike, following the virtual central road line while keeping his CoP stable [26]. The subjects were more efficient in stabilizing their CoP and thus in reducing their riding time in the condition without feedback than with it. These studies have thus demonstrated the improvement of the patients in their task by better controlling their weight shifting. Nevertheless, as for all the improvements obtained during training in VR, it is important to be cautious. A part of this progress can indeed be due to the mastery of the game. For instance, if the latency is perceptible, the subject has to move a little bit in advance to compensate it. By doing this, the subject will have better results in the game while not necessarily better controlling his weight shifting.

Finally, the last set of works that used VR without stereoscopic vision is composed of studies based on Motion Capture systems. These systems can be based on optical, inertial or depth sensors. They go from a simple video camera up to a complete optoelectronic system accurate to less than 1 mm.

Using background subtraction, Sveistrup et al. proposed a training program for Traumatic Brain Injury patients consisting of reaching for virtual objects, stepping, jumping, etc. [54]. Performance of patients in VR were measured with Community Balance and Mobility scale (CB&M) before and after the exercises and compared to a control group. On average, the patients in VR improved their CB&M more than three times compared to the control group. Still using background subtraction, Bisson et al. used both kinematical data and a force plate to create a game in which the subjects have to juggle with a virtual ball falling at different distances [7]. Movements of the older patients were recorded with a camera before background subtraction was applied. Several parameters were recorded before and after training, including functional balance and mobility CB&M, sway during quiet stance and reaction. The results showed an improvement of all subjects.

Kim et al. proposed using a Kinect to capture the motion of the elderly subjects and animate an avatar as feedback [31]. The rehabilitation was based on Tai Chi and Yoga and focused on the improvement of hip muscle strength and control balance over a period of 8 weeks. The results showed the effectiveness of their VR setup for rehabilitation.

Similarly, Lloréns et al. used a Microsoft Kinect and a screen (TV or LCD screen) to study the rehabilitation of patients suffering from residual hemiparesis after stroke [38]. The patients were divided into 2 groups: one was trained at home and the other in a clinical environment. The virtual environment was made up of an empty room with a chequered floor and various items appearing all around the virtual subject. Modifying the size and distance of objects, or their appearance duration could change the level of the exercise. Subjects had to touch items with their closest foot. The therapy lasted 8 weeks and balance was estimated before and after rehabilitation with BBS. The results showed that VR-based in clinic and VR-based telerehabilitation interventions offered both similar and significant improvement.

Everding et al. allowed 3 service members with upper and/or lower extremity amputations to guide a virtual boat using markers placed above the pelvis that are captured with a motion capture system (Vicon Inc., Oxford, United Kingdom) [16]. To better immerse the subject and enable different levels of difficulty, subjects stood on a moving platform that simulate the waves' movement. Performance was evaluated through the travel time of the boat over days of training. The 3 patients improved similarly, their performance following a power curve over days of training. Similarly, Hawkins et al. and Barton et al. immersed healthy subjects and children with diplegia in a virtual environment with a fantasy theme, made of flying carpet or dragons that moved simultaneously with markers placed on the pelvis and the trunk of the subjects. The subject must catch virtual items placed on the virtual environment in order to accelerate their displacement. Moreover, different initial positions can be tested (kneel sitting, high kneeling, standing) to modify the difficulty of the task [3,4,23]. The main idea of these studies is the analysis of the balance controlled by the pelvis and trunk trajectories. Some movements are executed with more control than others, highlighting weaknesses to explain a potential imbalance (since typically, rotation is better controlled than tilt, and single plane movements are executed with more control than cross plane movements). Introducing surface perturbation or accelerating speed enables the game to become harder and to fit as well as possible with the motor capacity of the subject.

Those studies provided a monitoring system that is adapted to the subject's level and enable a better understanding and improvement of the balance control. All patients improved after weeks of training, the level of difficulty of the games increasing over time.

Stereoscopic vision can increase the feeling of presence of immersion for the subject in VR; however this setup is more complex and requires more expensive devices. The simplest ones are HMD devices or a flat screen combined to stereoscopic glasses and video projector, but it can go up to a CAVE, a virtual environment composed of several walls surrounding the patient.

Lloréns et al. used their own low-cost system (BioTrak), a panoramic screen and stereoscopic glasses to immerse patients with brain injury in a virtual environment in which subjects have to reach virtual objects at various distances from them [36]. A simple and intuitive avatar that can be seen from a third-person viewpoint represents each subject. The movement of the subject can be captured with any tracking system and many parameters can be modified to adapt the difficulty of the simulation to the subject's pathology and morphology (resting time of the subject, number of repetitions, distance to the items, time they remain visible or size). All patients trained for 20 sessions of 20 minutes with exercises of increasing difficulty depending on their improvement. Balance was assessed at the beginning, at the end and one month after the end of the therapy by BBS and Performance-Oriented Mobility Assessment (POMA), but also with a NedSVE/IBV (a computerized posturography tool) dynamometric platform, which combines static posturography assessment with dynamic tests and provides a global index evaluating the balance. No control group was used, but still the results showed some significant improvements between initial and final balance measures that remain a month after the therapy. According to the subjects, BioTrack insures high degrees of presence, immersion and user-friendliness.

Kim et al. used the same protocol as [26] but with stereoscopic vision using an HMD device [30]. The subjects were on a bike and had to follow the central line while keeping their CoP as stable as possible. As for the study in monoscopic vision, the patients better performed their task after weeks of training by better controlling their weight shifting.

All these studies showed that patients improved during rehabilitation in VR, whatever the system used. Some authors even emphasized that the improvement is maintained after rehabilitation. Based on the positive results of these previous works, some authors have proposed using VR not only to assess the rehabilitation of balance but to classify patients in 2 classes: healthy and unhealthy. Yeh et al. proposed to evaluate the difference of progress of 2 populations: patients suffering from vestibular dysfunction and healthy patients [58]. They analyzed the subject's motion captured with a Microsoft Kinect device and the statokinesigram acquired with a Nintendo Wii Fit. Several various VR exercises were proposed to evaluate specific performance such as bilateral coordination, eye and head movements and balance. Their results showed significant progresses for the patients after rehabilitation but more interestingly they discriminate the two populations, through using the Support Vector Machine (SVM), by learning the variations of parameters according to these two populations. This work not only confirms the positive effect of VR on rehabilitation but also proposes the use of VR for pathology detection and assessment. This work must therefore be extended to better quantify the degree of pathology of a patient.

Conclusion

VR is now commonly used in many domains, especially in the medical field, where balance assessment and rehabilitation can benefit from its standardized, reproducible and controllable features. Nevertheless, VR is based on software and hardware that computes the virtual environment and renders it. This means that it cannot provide a perfectly realistic environment, but more problematically, may modify the perception and the interaction with this virtual environment. Thus, VR also has main limitations that are sometimes omitted or understated. The first one is the latency, that is, the delay between the actions of the immersed patient with input devices and the reaction of the virtual environment and thus the change of the stimuli presented to this patient. Concerning balance assessment, this delay creates a sensory conflict that can lead to nausea or falling. Moreover, when dealing with reaction times, for instance to evaluate the sway velocity or the Anticipatory Postural Adaptation of a patient who avoids a virtual projectile, the sensors equipped on the patient must be synchronized with the launch of this virtual projectile. It is technologically difficult to setup and the results strongly depend on the latency of the system since the reaction of the patient is added to the delay between the computation of the ball and the perception of the visual stimulus. Latency must then be taken into account when the results have to be compared to real data, from the literature for instance. The second limit of VR is the underestimation of perceived distance in virtual environments compared to real situations. The problem arises when the parameters of the patients' performance are compared between real and virtual situations. In this review, we described a case study to emphasize the advantages and limits of VR for balance assessment. The results showed a temporal shift of the data and a bigger displacement of the CoP. It could be interesting to determine the relative influence of latency and distance perception in the alteration of the data and to quantify the minimum acceptable thresholds. In the context of balance rehabilitation, the studies usually compare data before and after the rehabilitation. VR is then considered as a training tool and the goal is to evaluate the evolution of the patient. The limits are then less problematic since the parameters of evaluation are the same before and after the rehabilitation.

To conclude, many studies have used VR for balance assessment and rehabilitation. The ability to control all the parameters of the simulation offers an infinite number of configurations. This allows an accurate evaluation of each factor responsible of balance or its loss but also the comparison of the relative weight of each sense using sensory conflict studies. It also provides a new generation of rehabilitation tools and at the same time a way to assess the efficiency of these tools in order to optimize them. However, only a few papers have evaluated the influence of the limits of VR on balance rehabilitation and assessment tasks as has been done in other domains such as locomotion.

A very large majority of papers use visual perception and proprioception in their studies. VR can have various input and output devices such as haptic, sound, etc. For instance, Milosevic and McConville used the combination of visual and auditory feedbacks [43] to evaluate postural control. Many studies could be made to go further and evaluate the contribution of more complex VR systems. Adding real time feedback can complete the spectrum of the features available. Nevertheless, this requires more engineering skills because of the complexity of the setups. A multidisciplinary approach will provide promising new studies in the field of balance assessment and rehabilitation over the coming years.

Disclosure of interest

The authors have not supplied their declaration of competing interest.

References

[1] Agmon M, Perry C, Phelan E, Demiris G, Nguyen H. A pilot study of Wii Fit exergames to improve balance in older adults. J Geriatr Phys Ther 2011;161:167.

[2] Akiduki H, Nishiike S, Watanabe H, Matsuoka K, Kubo T, Takeda N. Visual-vestibular conflict induced by virtual reality in humans. Neurosci Lett 2003;340(3):197—200.

[3] Barton GJ, Hawken MB, Foster RJ, Holmes G, Butler PB. Playing the Goblin Post Oce game improves movement control of the core: a case study. IEEE Virtual Rehabilitation (ICVR); 2011 [15 pages].

[4] Barton GJ, Hawken MB, Foster RJ, Holmes G, Butler PB. The effects of virtual reality game training on trunk to pelvis coupling in a child with cerebral palsy. J Neuroeng Rehabil 2013;10(1):15.

[5] Bideau B, Kulpa R, Ménardais S, Fradet L, Multon F, Delamarche P. Real handball goalkeeper vs. virtual handball thrower. Presence 2003;12(4):411—21.

[6] Bideau B, Kulpa R, Vignais N, Brault S, Multon F, Craig C. Using virtual reality to analyze sports performance. IEEE Comput Graph Appl 2010;30(2):14—21, http://dx.doi.org/10.1109/MCG. 2009.134.

[7] Bisson E, Contant B, Sveistrup H, Lajoie Y. Functional balance and dual-task reaction times in older adults are improved by virtual reality and biofeedback training. Cyberpsychol Behav 2007;20(1).

[8] Booth V, Masud T, Bath-Hextall F. The effectiveness of virtual reality interventions in improving balance in adults with impaired balance compared with standard or no treatment: a systematic review and meta-analysis. Clin Rehabil 2014;28(5):419—31.

[9] Bugnariu N, Fung J. Aging and selective sensorimotor strategies in the regulation of upright balance. J Neuroeng Rehabil 2007;4(1):19.

[10] Chiavorano E, de Waele C, MacDougall H, Rogers S, Burgess A, Curthoys I. Maintaining balance when looking at a virtual reality three-dimensional display of a field of moving dots or at a virtual reality scene. J Front Neurol 2015.

[11] Cho KH, Lee KJ, Song CH. Virtual-reality training with videogame system improves dynamic balance in chronic stroke patients. Tohoku J Exp Med 2012;228:69—74.

[12] Cikajlo I, Rudolf M, Goljar N, Matjacic Z. Virtual reality task for telerehabilitation dynamic balance training in stroke subjects. In: IEEE Virtual Rehabilitation International Conference. 2009.

[13] Cikajlo I, Rudolf M, Goljar N, Burger H, Matja£i¢ Z. Telerehabilitation using virtual reality task can improve balance in patients with stroke. Disabil Rehabil 2012;34(1):13—8.

[14] Darekar A, McFadyen BJ, Lamontagne A, Fung J. Efficacy of virtual reality-based intervention on balance and mobility disorders post-stroke: a scoping review. J Neuroeng Rehabil 2015;12:46.

[15] Eikema D, Hatzitaki V, Tzovaras D, Papaxanthis C. Age-dependent modulation of sensory reweighting for controlling posture in a dynamic virtual environment. Age 2012;34(6):1381—92.

[16] Everding VQ, Kruger SE. Virtual reality enhanced balance training for service members with amputations. Virtual Rehabil 2011.

[17] Gérin-Lajoie M, Richards CL, Fung J, McFadyen BJ. Characteristics of personal space during obstacle circumvention in physical and virtual environments. Gait Posture 2008;27(2):239—47.

[18] Gil-Gomez JA, Lloréns R, Alcañiz M, Colomer C. Effectiveness of a Wii balance board-based system (eBaVir) for balance rehabilitation: a pilot randomized clinical trial in patients with acquired brain injury. J Neuroeng Rehabil 2011;8:30.

[19] Greffou S, Faubert J. Life-span study of visually driven postural reactivity: a fully immersive virtual reality approach. J Vis 2008;8(6):426.

[20] Greffou S, Bertone A, Hanssens J-M, Faubert J. Development of visually driven postural reactivity: a fully immersive virtual reality study. J Vis 2008;8(11):15.

[21] Hamilton EC, Scott DJ, Fleming JB, Rege RV, Laycock R, Bergen PC. Comparison of video trainer and virtual reality training systems on acquisition of laparoscopic skills. Surg Endosc Interv Tech 2002;16(3):406—11.

[22] Hanssens JM, Piponnier JC, Faubert J. Influence of central and peripheral visual field on the postural control when viewing an optic flow stimulus. J Vis 2010;8(6):858.

[23] Hawkins P, Hawken M, Barton G. Effect of game speed and surface perturbations on postural control in a virtual environment. In: Proceeding of the 7th ICDVRAT. 2008. p. 311—8.

[24] Hendrix C, Barfield W. Presence within virtual environments as a function of visual display parameters. Presence 1996;5(3):274—89.

[25] Horlings C, Carpenter MG, Küng UM, Honegger F, Wiederhold B, Allum J. Influence of virtual reality on postural stability during movements of quiet stance. Neurosci Lett 2009;451(3):227—31.

[26] Jeong SH, Piao YJ, Chong WS, Kim YY, Lee SM, Kwon TK. The development of a new training system for improving equilibrium sense using a virtual bicycle simulator. Conf Proc IEEE Eng Med Biol Soc 2005:2567—70.

[27] Jones A, Swan JE, Singh G, Kolstad E. The effects of virtual reality, augmented reality, and motion parallax on egocentric depth perception. 2008:267—8.

[28] Keshner EA, Kenyon RV. Influences on postural orientation in a virtual environment. Complex Med Eng 2007:1307—10.

[29] Keshner EA, Kenyon RV, Dhaher Y. Postural research and rehabilitation in an immersive virtual environment. Eng Med Biol Soc 2004;4:4862—5.

[30] Kim NG, Yoo CK, Im JJ. A new rehabilitation training system for postural balance control using virtual reality technology. IEEE Trans Rehabil Eng 1999;7(4):482—5.

[31] Kim J, Son J, Ko N, Yoon B. Unsupervised virtual reality-based exercise program improves hip muscle strength and balance control in older adults: a pilot study. Arch Phys Med Rehabil 2013;94:937—43.

[32] Kosse NM, Caljouw SR, Vuijk P, Lamoth C. ExergamIng: interactive balance training in healthy community dwelling older adults. J Cybertherapy Rehabil 2011.

[33] Lee HY, Cherng RJ, Lin CH. Development of a virtual reality environment for somatosensory and perceptual stimulation in the balance assessment of children. Comput Biol Med 2004;34:719—33.

[34] Levac D, Espy D, Fox E, Pradhan S, Deutsch JE. ''Kinect-ing'' with clinicians: a knowledge translation resource to support decision making about video game use in rehabilitation. Phys Ther 2015;95(3):426—40.

[35] Li Z, Han XG, Sheng J, Ma SJ. Virtual reality for improving balance in patients after stroke: a systematic review and meta-analysis. Clin Rehabil 2015.

[36] Lloréns R, Colomer-Font C, Alcañiz M, Noé-Sebastián E. BioTrak virtual reality system: effectiveness and satisfaction analysis for balance rehabilitation in patients with brain injury. Neurologia 2013;28(5):268—75.

[37] Lloréns R, Albiol S, Gil-Gómez J, Alcañiz M, Colomer C, Noé E. Balance rehabilitation using custom-made Wii Balance Board exercises: clinical effectiveness and maintenance of gains in an acquired brain injury population. Int J Disabil Hum Dev 2014;13(3).

[38] Lloréns R, Noé E, Colomer C, Alcañiz M. Effectiveness, usability, and cost-benefit of a virtual reality based telerehabilitation program for balance recovery after stroke: a randomized controlled trial. Arch Phys Med Rehabil 2015;96(3):418—25.

[39] Meldrum D, Herdman S, Moloney R, Murray D, Duy D, Malone K. Effectiveness of conventional versus virtual reality based vestibular rehabilitation in the treatment of dizziness, gait and balance impairment in adults with unilateral peripheral vestibular loss: a randomised controlled trial. BMC Ear Nose Throat Disorders 2012;12(1):3.

[40] Meldrum D, Glennon A, Herdman S, Murray D, McConn-Walsh R. Virtual reality rehabilitation of balance: assessment of the usability of the Nintendo Wii R Fit Plus. Disabil Rehabil 2012;7(3):205—10.

[41] Meldrum D, Herdman S, Vance R, Murray D, Malone K, Duy D. Effectiveness of conventional versus virtual reality-based balance exercises in vestibular rehabilitation for unilateral peripheral vestibular loss: results of a randomised controlled trial. Arch Phys Med Rehabil 2015.

[42] Mendes F, Pompeu JE, Lobo AM, da Silva KG, de Paula Oliveira T, Zomignani AP, et al. Motor learning, retention and transfer after virtual-reality-based training in Parkinson's disease effect of motor and cognitive demands of games: a longitudinal, controlled clinical study. Physiotherapy 2012;98(3):217—23.

[43] Milosevic M, McConville K. Audio-visual biofeedback system for postural control. Int J Disabil Hum Dev 2011;10(4):321—4.

[44] Nishiike S, Okazaki S, Watanabe H, Akizuki H, Imai T, Uno A, et al. The effect of visual-vestibulosomatosensory conflict induced by virtual reality on postural stability in humans. J Med Invest 2013;60(3.4):236—9.

[45] Parsons DT, Rizzo AA. Affective outcomes of virtual reality exposure therapy for anxiety and specific phobias: a meta-analysis. J Behav Ther Exp Psychiatry 2008;39(3):250—61.

[46] Piponnier JC, Hanssens JM, Faubert J. Effect of visual field locus and oscillation frequencies on posture control in an ecological environment. J Vis 2009;9(1):13.

[47] Price M, Anderson P, Rothbaum BO. Virtual reality as treatment for fear of flying: a review of recent research. Int J Behav Consult Ther 2008;4(4):340—7.

[48] Renner RS, Velichkovsky BM, Helmert JR. The perception of egocentric distances in virtual environments — a review. ACM Comput Surv 2013;46(2).

[49] Sanchez-Vives M, Slater M. Opinion: from presence to consciousness through virtual reality. Nat Rev Neurosci 2005;6(4):332—9.

[50] Slater M, Linakis V, Usoh M, Kooper R. Immersion, presence and performance in virtual environments: an experimental with tridimensional chess. In: Green M, editor. Virtual reality software and technology. Hong Kong: ACM Press; 1996. p. 163—72.

[51] Slater M, Khanna P, Mortensen J, Yu I. Visual realism enhances realistic response in an immersive virtual environment. IEEE Comput Graph Appl 2009;29(3):76—84.

[52] Smith ST, Schoene D. The use of exercise-based videogames for training and rehabilitation of physical function in older adults. Aging Health 2012;8(3):243—52.

[53] Standen PJ, Threapleton K, Connell L, Richardson A, Brown DJ, Battersby S, et al. Patients' use of a home-based virtual reality system to provide rehabilitation of the upper limb following stroke. Phys Ther 2015;95(3):350—9.

[54] Sveistrup H, McComas J, Thornton M, Marshall S, Finestone H, McCormick A. Experimental studies of virtual reality-delivered compared to conventional exercise programs for rehabilitation. Cyberpsychol Behav 2003;6(3).

[55] Tarr M, Warren W. Virtual reality in behavioral neuroscience and beyond. Nat Neurosci 2002;5:1089—92.

[56] Tossavainen T, Juhola M, Pyykkö I, Aalto H, Toppila E. Development of virtual reality stimuli for force platform posturography. Int J Med Inform 2003;70(2—3):277—83.

[57] Yang WC, Wang HK, Wu RM, Lo CS, Lin KH. Home-based virtual reality balance training and conventional balance training in Parkinson's disease: a randomized controlled trial. J Formos Med Assoc 2005.

[58] Yeh SH, Huang MC, Wang PC, Fang TY, Su MC, Tsai PY, et al. Machine learning-based assessment tool for imbalance and vestibular dysfunction with virtual reality rehabilitation system. Comput Methods Programs Biomed 2014;116(3):311—8.

[59] Yen CY, Lin KH, Hu MH, Wu RM, Lu TW, Lin CH. Effects of virtual reality-augmented balance training on sensory organization and attentional demand for postural control in people with Parkinson disease: a randomized controlled trial. Phys Ther 2011;91(6):862—74.

[60] Yiannakopoulou E, Nikiteas N, Perrea D, Tsigris C. Virtual reality simulators and training in laparoscopic surgery. Int J Surg 2015;13:60—4.