Wearable virtual reality tool for balance training: the design and validation on healthy[*]

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Abstract. Balance disabilities affect the human quality of life. Current directions for balance rehabilitation require the inclusion of virtual reality (VR) tools as a complementary robotic tool to conventional physical therapies to accelerate balance recovery. This works aims to present the design and validation on healthy of a wearable and fully immersive VR-based tool following a user-centred design. This wearable VR tool comprises four Activities of Daily Living-based virtual challenges including nine motor tasks, chosen according to those most performed in the literature, as well as in the tasks of the Berg Balance Scale (BBS) and Timed Up and Go (TUG) clinical tests. This system comprises wearable VR technology, providing multimodal feedback (visual, sonorous, and vibrotactile cues), and integrates wearable inertial sensors for real-time motor assessment. The system's operability was validated with six healthy subjects executing BBS and TUG related motor tasks to assess balance performance after and before two training trials for each virtual challenge. The results showed statistically significant improvements regarding COM' displacement and velocity during "Cooking" and "Watch Tv" games and after VR training. The VR-based tool was rated with high IPQ and IMI scores. This wearable VR-based tool has the potential to effectively improve balance and walking, and to effectively increase the user's active participation and enthusiasm during balance training; thus, contributing to accelerate the user's balance and motor recovery.

Keywords: ADLs, wearable inertial system, user-centred design.

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1 Introduction

Balance disability is one of the main risk factors for falling, being the second leading cause of unintentional injury deaths worldwide [1]. It is mainly caused by neurological conditions (i.e., stroke, Parkinson's disease, cerebral palsy), ear disorders (i.e., ear infections, vestibular problems as inner ear abnormalities or Meniere's disease), head injury, age (>= 60 years old), or medication [2], [3]. The loss of balance itself and the associated fear of falling lead to loss of independence and increased difficulty to perform Activities of Daily Living (ADLs), compromising quality of life, and professional and social inclusion [4].

People left disabled can recover balance function and regain their motor independence through rehabilitation intervention, either physical or robotic [5], [6]. Physical therapy, as conventional rehabilitation intervention, has the disadvantages of being non-standard and dependent on the therapist's experience [5], [6]. Robotic therapy includes robotic devices to objectively assess user's motor condition and provide personalized intensive and repetitive training according to user's needs [7], [8]. Virtual reality (VR)-based tools are promising in robotic rehabilitation once they offer endless three-dimensional (3D) virtual reality environments (VREs), eliciting realistic perceptions and reactions in the user [9]–[11]. VR tools have the advantage of evolving the users in a multi-sensory, fully immersive, and enthusiast VREs designed and customised according to the user's imminent needs [12]. Thus, increasing user's active participation leading to accelerate balance recovery [12]. VR intervention has already been shown to be effective for improving balance [13]–[17]. A literature review was conducted on this topic [15], concluding that most of studies use non-wearable VR technology and biosensors, limiting the clinical practice of the VR tools to an indoor fixed facility [14]–[16]; there is a lack of fully immersive VR systems for balance training; and, none VR tool suggests a user-centred design not having into account the users' most performed and appreciated ADLs for designing the tool [15], [16]; and, no study mention to choose VR-encouraged motor tasks according to the clinically accepted BBS and TUG clinical tests for balance assessment [15], [16].

This work aims to present the user-centred design and validation on healthy of a wearable and fully immersive VR tool for balance training, having into account the most performed and appreciated ADLs and BBS and TUG-related motor tasks during the design. Thus, it contributes with a novel wearable and fully immersive VR-based tool for BBS and TUG-related motor tasks training while virtually performing the most performed and appreciated ADLs, and the evidence concerning its kinematic effects and user's experience evaluation on healthy. Firstly, the VR technology, sensor integration for objective motor assessment, four virtual challenges and related VRE and motor tasks are described. Secondly, six control strategies that allow the users to interact with the VRE and provide real-time feedback are shown. Thirdly, the experimental validation with healthy subjects and the related results are presented and discussed.

2 Methods

2.1 VR technology

The VR commercial device HTC Vive Pro Full Kit (HTC VIVE Pro, HTC, Taiwan, Republic of China) was used to allow the fully immersion and interaction of the user with the VRE within a play area of 2 m x 1.5 m. Beyond being wearable, fully immersive, and portable, the system's ability to provide multimodal feedback (visual, auditory, and vibrotactile cues) also motivated its selection once improves the user's sense of presence [18]. A computer Republic of Gamers Strix Helios with a NVIDIA GeForce RTX 3080 Ti GPU was used to run the software needed by the VR-based tool. A monitor screen was also used so that the training can be followed by accompanying persons as physiotherapists, allowing to track in real-time the users' performance during the balance training and, consequently, provide additional support according to their imminent needs.

2.2 Sensor integration

The wearable inertial measurement unit-based motion capture system MVN Awinda (Xsens, Enschede, Netherlands) was integrated into the VR-based tool given its reliability for body motion analysis in free-living conditions. This system was used in a full body suit configuration. After a successful calibration, the "Position + Orientation (Quaternion)" and "Centre of Mass" (COM) data were selected to be streamed in real-time to the third-party software used to develop the VRE at 100 Hz using UDP communication protocol. Its wearability and portability make it ideal for training in any location, potentiating daily practice and, thus, accelerating the recovery process.

2.3 Motor tasks

The motor tasks encouraged by the VR tool were chosen based on the literature and BBS and TUG clinical tests which are the most performed tests for balance assessment in clinical practice [15]. So, while using this tool for balance training, the users are practicing the motor tasks clinically accepted and performed in conventional physical rehabilitation, allowing to increase the tool's acceptability. The chosen nine motor tasks were: 1) walking; 2) stepping; 3) sit-to-stand and stand-to-sit; 4) knee flexion and extension; 5) weight-shifting; 6) trunk and pelvic/hip movement; 7) look over the shoulder; 8) standing upright on one leg; 9) reaching.

2.4 Virtual challenges and VRE

Four virtual challenges based on ADLs – "Fruit Catcher", "Cooking", "Take a Shower", and "Watch TV" - were proposed to enthusiasm the physical training. They match the most performed and appreciated ADLs that require balance according to the answers of a questionnaire completed by 64 persons described in [19]. Unity 3D software, Unity Technologies (Copenhagen, Denmark), was used to develop the VRE. It consists of a house with detailed indoor and outdoor spaces designed to be the most realistic and immersive as possible. Natural ambient sound and ambient sunlight were also created.

Fruit Catcher. Its VRE consists of a backyard with a tree, a ladder, and apples as main objects to carry out the virtual game (Fig. 1). The "Fruit Catcher" game aims that the user: 1) climbs six steps of the ladder perched on the tree through stepping with each foot alternately; 2) then, reach and catch nine apples, three forwards and three to each side left and right by performing weight shifting (with their feet together and without moving them) looking forwards and over the left and right shoulders, respectively. The nine apples were placed at predefined distances (5 cm, 12.5 cm, and 25 cm after the hand position with arms outstretched of a person with 1.70 m height) corresponding to the second, third, and fourth levels of the eighth BBS' task (entitled "Reaching forward with outstretched arm while standing"), respectively.

Cooking. For this virtual challenge, a kitchen division was created, with special emphasis on the four shelves full of ingredients (Fig. 1). The "Cooking" game aims that the user, with their feet together and without moving them, reaches six ingredients at specific points of the shelves: 1) three levels of height adjusted according to user's height (2 ingredients/level) through knee and hip flexion and extension; 2) on the left and right sides (3 ingredients/side) by performing weight shifting. The user is asked to put individually the ingredients in the basket beside her/him, keeping her/his balance.

Take a Shower. A bathroom division with special focus on the bathtub with a height of 40 cm (standard height of an undermount real bathtub [20]) was created (Fig. 1). The "Take a Shower" game aims that the user: 1) firstly, enters the bathtub with one foot at a time through knee flexion and extension without listening a sound of a kicking that is generated every time she/he touches the bathtub's rim; 2) once inside the bathtub, stands upright on one leg for listening to a sound of running water (auditory feedback) in case of success in lifting the leg enough, mimicking that she/he is washing her/himself. The user must lift the leg at least 25 cm and stand upright on one leg for at least 10 s (time to reach the maximum score on fourteenth BBS's task entitled "Standing on one leg") to achieve the maximum score.

Watch Tv. A living room with special emphasis on the television and sofa, designed with a height of 47 cm according to the standards of real chairs [21], was created (Fig. 1). The "Watch Tv" game was inspired by the TUG-related motor tasks. In this game, the user, initially raised, must: 1) sit in the virtual sofa (supported by a real matched chair); 2) stand; 3) walk 3 meters forward towards the television until it turns on; 4) rotate 180 degrees; 5) walk again 3 meters towards the sofa, ending the game. A video (visual and auditory feedback) plays on the television when the user reaches the 3 meters forward the sofa. The sit-to-stand and stand-to-sit tasks were performed in a different order when compared to the real TUG to ensure the user's safety.

Fig. 1. Design of house backyard (upper left), kitchen (upper right), bathroom (lower left), and living room (lower right).

2.5 Control strategies

Six control strategies were created to allow the user to interact with the VRE and receive feedback from it, namely: 1) first and second person views (available during all serious games); 2) grab; 3) vibrotactile feedback; 4) visual and auditory feedback; 5) stepping up the ladder; 6) shelves height.

A **first-person perspective** was implemented by matching the position tracking from the headset and controllers with an avatar mimicking in real-time the user's body movement through the "MVN Live Animation" Unity plug-in (Fig. 2). A **second-person perspective** showing in real-time the user's feet with her/his COM projected was also created (Fig. 2). The COM is represented by one red ball (diameter of 1 cm) placed at feet level to easily visualize if it is within the base of support (area that includes every point of contact that the person makes with the supporting surface and, in the case of having more than one point contact, the area between them too) [22]. The position of the virtual red ball was controlled according to the streamed COM data post-transformed from the MVN to the Unity reference axes. Thus, the user can adjust her/his posture during VR training towards maintaining balance and preventing her/him from falling.

Fig. 2. First person view during "Watch Tv" virtual challenge with the second person view highlighted by the orange square.

Grab control strategy allows the apples on the tree and the ingredients placed on the shelves to be caught with the HTC controllers, if they are not static objects and have physical properties. This strategy was associated to both controllers' Trigger button by configuring "Open binding UI" to add "Grab" action on "SteamVR Input". **Vibrotactile feedback** occurs when user grabs or collides with virtual objects (as the apples on the tree and the food placed on the shelves) with "Box Colliders" and "OnTriggerEnter" components using HTC controllers. The vibrotactile cues are generated by the controllers with haptic amplitude, duration, and frequency of 88 g, 0.4 s, and 22 Hz, respectively, by configuring "Open binding UI" to add "Haptic" action.

In "Watch Tv" game, a video (**visual and auditory feedback**) plays in the Tv screen when the avatar's collider enters in the television's collider. For "Take a Shower" game, a sound (**auditory feedback**) imitating a kick against the wall is enabled every time the user touches the bathtub' wall, by creating colliders on the stone of the bathtub and on the user's right and left feet. Also, a sound of running water (**auditory feedback**) plays each time the height of user's foot (assessed through "Position + Orientation" streamed data) is above 25 cm from floor and stops 10 s after it or if the user puts her/his foot below the threshold value.

In "Fruit Catcher" game, the avatar **steps up the ladder** perched in the tree by moving up and forward the vertical and horizontal position of the avatar every time the height of right or left user's foot is above 25 cm from the floor and backs to the floor's height. The **height of the shelves** in "Cooking" game was automatically customised according to the user height by agreement with standard measures of kitchen shelves and ergonomic rules [23].

2.6 Experimental validation

The validation protocol was conducted following the principles of the Declaration of Helsinki and Oviedo Convention, and approved by the local ethical committee CEICVS 006/2020 at University of Minho. Six healthy participants (gender: 3 females, age: 23.67 ± 0.94 years, height: 1.66 ± 0.09 m, body mass: 62.93 ± 10.65 kg) were recruited and signed an informed consent to participate in the validation protocol. They were instructed to execute BBS and TUG-related motor tasks to assess balance performance after and before VR training. The VR training included 2 trials in a row per virtual challenge (randomly ordered) with a maximum duration of 3 min each and 3 min of rest between trials. The participants self-selected the order to pick up the apples and the ingredients in the virtual challenges "Fruit Catcher" and "Cooking", respectively. The participants were accompanied during the entire protocol to ensure their safety.

Sensor-based assessment were performed before, during, and after the VR training using Xsens inertial system. The outcomes during VR intervention and the BBS and TUG-related motor tasks are the COM's position and velocity in the anteroposterior (AP) and mediolateral (ML) directions. After the intervention, all participants answered the Intrinsic Motivation Inventory (IMI) and Igroup Presence Questionnaire (IPQ) to evaluate the user's experience. The IPQ questionnaire evaluates the VR tool in terms of the VRE's realism and how engaged the participant feels by it and IMI questionnaire assesses the experience lived by the user while using the VR-based tool to complete the virtual challenges. After processing, COM displacement and minimum and maximum COM velocity on the AP and ML directions were obtained.

The statistical analysis included the two-tailed *t*-tests and Wilcoxon signed-rank tests for parametric and non-parametric metrics, respectively, using the IBM SPSS software version 26.0 (IMP Corp, Armonk, NY, USA). The statistical tests were conducted to evaluate the following null hypotheses: 1) there are no statistically significant differences between trial 1 and trial 2 of VR intervention; 2) there are no statistically significant differences between before and after VR intervention.

3 Results

3.1 During VR intervention

During VR intervention, maximum COM's velocity in AP direction statistically significant decreased from T1 to T2 of "Cooking" game (Table 1). In "Watch Tv" game, the COM's displacement in ML direction and the minimum COM's velocity in AP direction during walking statistically significantly decreased and increased, respectively (Table 1). The virtual challenges "Fruit Catcher" and "Take a Shower" did not present statistically significant differences between T1 and T2 (*p*-value > 0.05).

Table 1. Mean and standard deviation (SD) of trial 1 (T1) and trial 2 (T2), and the *p*-value of the statistical test for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions revealing statistically significant differences, considering a significance level of 5%

Virtual challenge Outcome	**Mean ± SD** T1	 T2	***p*-value**
Cooking			
VelMaxAP	11.008 ± 1.769	7.985 ± 0.857	**.027**
Watch Tv			
DispMLWalk	9.113 ± 0.982	7.483 ± 0.553	**.049**
VelMinAPWalk	42.647 ± 3.259	46.773 ± 3.836	**.020**

3.2 Before vs after VR intervention

By comparing the balance performance before versus after the VR intervention, statistically significant differences were found for the following BBS's tasks: sit-to stand, stand-to-sit, transfers, standing with eyes closed, standing with feet together, reaching forward, and standing on one leg, and for TUG's task during walking (Table 2). The BBS's tasks standing unsupported, sitting unsupported, pick up an object, looking over shoulders, turn 360 degrees, place alternate foot on step, and standing with one foot in front did not present statistically significant differences between pre and post VR training (*p*-value > 0.05).

Table 2. Mean and standard deviation (SD) of pre and post VR training, and the *p*-value of the statistical test for COM displacement (Disp), and maximum (Max) and minimum (Min) COM velocity (Vel), on AP and ML directions revealing statistically significant differences, considering a significance level of 5%

Motor task Outcome	**Mean ± SD** Pre	 Post	***p*-value**
Sit-to-stand (BBS)			
DispAP	42.235 ± 1.445	37.548 ± 2.344	**.047**
Stand-to-sit (BBS)			
DispAP	40.058 ± 1.844	35.810 ± 2.045	**.011**
VelMaxAP	2.472 ± 0.453	3.663 ± 0.631	**.041**
Transfers (BBS)			
VelMinAP	-38.720 ± 2.442	-41.933 ± 2.678	**.030**
Standing with eyes closed (BBS)			
VelMinAP	-2.017 ± 0.610	-1.635 ± 0.576	**.018**
VelMaxAP	1.090 ± 0.179	1.270 ± 1.184	**.022**
Standing with feet together (BBS)			
DispML	1.313 ± 0.093	1.565 ± 0.145	**.046**
VelMaxML	1.143 ± 0.174	1.792 ± 0.517	**.046**
Reaching forward (BBS)			
DispAP	9.773 ± 0.949	8.365 ± 0.934	**.001**
Standing on one leg (BBS)			
VelMinAP	-3.853 ± 0.670	-2.853 ± 0.471	**.032**
Walking (TUG)			
VelMaxAP	120.197 ± 3.172	113.738 ± 3.866	**.047**

3.3 User's experience evaluation

The VR-based tool proved to be well accepted by the users, who experienced a sense of presence, realism, and involvement by the created VRE (Table 3). It was also proved that the participants were interested during the VR intervention and felt highly competent while performing the virtual challenges (Table 4). For the three open-ended questions of the IMI questionnaire, participants reported that the tool seems useful for improving balance once it helps them to understand their limits in posture and balance (participant 6), to increase balance and trunk mobility (participant 5), and to recover from physical injuries of the lower body (participant 4).

Table 3. Mean and standard deviation (SD) of all participants and best score for each factor of IPQ

	Spatial Presence	Involvement	Experienced Realism	Global Presence
Mean ± SD	4.25 ± 0.53	3.58 ± 0.45	3.88 ± 0.24	3.90 ± 0.24
Best score	6.33/7.00	6.00/7.00	7.00/7.00	6.44/7.00

Table 4. Mean and standard deviation (SD) of all participants and best score for each subscale of IMI

	Interest/ Enjoyment	Perceived Competence	Effort/ Importance	Pressure/ Tension	Value/ Usefulness
Mean ± SD	5.81 ± 0.61	5.53 ± 0.58	5.27 ± 0.98	3.03 ± 1.53	5.33 ± 0.84
Best score	7.00/7.00	7.00/7.00	2.20/7.00	1.00/7.00	7.00/7.00

4 Discussion

This work proposes a novel wearable VR-based tool for balance training allowing their use in a non-fixed facility in opposite to most current literature [14]–[16]. The VR technology included provides fully immersion of the user in the VRE enabling the most realistic training in opposite to [17]. Sensors were integrated into the VR-based tool for objective assessment of user's motor performance preventing dependence on physiotherapist's experience in clinical practice as in [17]. Nine motor tasks included in the clinically accepted most performed clinical tests for balance assessment (BBS and TUG) are encouraged during the proposed VR training so that the users can efficiently improve their balance ability [15], [16]. Following a user-centred design, the VR training implies virtual challenges that correspond to the most performed and appreciated ADLs, increasing the enthusiasm during training and the impact in users' daily life [15], [16], [20]. Six control strategies were developed to provide multimodal feedback and allow users' interaction with the VRE, fostering their sense of presence and active participation, respectively, as in [24].

The VR-based tool was preliminary validated with six healthy subjects evaluating the kinematic effects regarding COM's displacement and velocity before, during, and after VR training and the qualitative assessment of user's experience. During "Cooking" training, the maximum COM velocity in AP direction decreased from T1 to T2. However, COM velocity in ML direction did not statistically significantly decrease, being the ML direction more encouraged than AP direction due to lateral weight-shifting. Regarding the "Watch Tv" training, the results suggest a balance improvement in both ML and AP directions once the COM's displacement decreased and the minimum

COM's velocity increased from T1 to T2, respectively. Therefore, the users improved their side-to-side movement control (more stable balance) and were able to move faster during walking.

Regarding the kinematic effects before versus after VR training, in sit-to-stand and stand-to-sit tasks (related to "Cooking" and "Watch Tv" games), the decrease of COM's displacement in the AP direction means that after VR training participants were able to perform these tasks with greater stability of the movement. The increase of maximum COM's velocity in stand-to-sit task represents a faster forward movement when participants lean before sitting. When performing transfers between chairs, participants shown an improvement of minimum COM's velocity, indicating that they were able to perform this motor task faster without losing balance. While standing with eyes closed, participants decreased in module the minimum but increased the maximum COM's velocity in the AP direction. Cho et al. [25] also showed improvements in postural sway velocity in the AP direction, although not significant. For standing with feet together, participants decreased the maximum COM's velocity but increased the COM's displacement in the ML direction. The negative results of standing with eyes closed and standing with feet together motor tasks can be explained by the lack of static motor task in the developed VR-based tool. For the task of reaching forward (related to "Fruit Catcher" game), the participants were able to reach the same object with greater stability and balance after VR training once the COM's displacement decreased in AP direction. Further, in standing on one leg (related to "Take a Shower" game), it was reported a module decrease of minimum COM velocity in ML direction, indicating greater stability. Regarding walking (related to "Watch Tv" game), the decrease of the maximum COM's velocity in AP direction may be related to the reduced space to walk (3 meters each way) being difficult for people to increase speed and, thus, giving priority to a slower gait. Although the healthy ability of the participants and the reduced number of training trials, balance improvements were registered during and before vs after VR training.

The users experienced high (>3.50) spatial presence, involvement, realism, and global presence. Moreover, they reported high (>3.50) Interest/Enjoyment and Perceived Competence. Despite the high Effort/Importance, they reported feeling low Pressure/Tension. In addition, they also allocated it a high Value and Usefulness for improving balance. Thus, findings point out that the tool seems promising for balance rehabilitation, complementing conventional physical therapy.

5 Conclusion

This work presents a wearable and fully immersive VR-based tool for balance training following a user-centred design. The tool integrates inertial sensors for real-time objective assessment of users' motor performance. Furthermore, it includes multimodal feedback, providing visual, auditory, and vibrotactile cues, through HTC HMD, their built-in headphones, and controllers, respectively. The VR training comprises ADL-based four virtual challenges to encourage the execution of BBS and TUG-related motor tasks. The results from the preliminary validation with six healthy subjects demonstrate statistically significant improvements regarding COM' displacement and velocity during "Cooking" and "Watch Tv" games and after VR training. The VR-based tool was rated with high IPQ and IMI scores. Future work comprises a feasibility study with balance injured patients.

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