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Evaluating Balance Recovery Techniques for Users Wearing Head-Mounted Display in VR

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Stephen Lord, and Chin-Teng Lin

Abstract—Room-scale 3D position tracking enables users to explore a virtual environment by physically walking, which improves comfort and the level of immersion. However, when users walk with their eyesight blocked by a head-mounted display, they may unexpectedly lose their balance and fall if they bump into real-world obstacles or unintentionally shift their center of mass outside the margin of stability. This paper evaluates balance recovery methods and intervention timing during the use of VR with the assumption that the onset of a fall is given. Our experiment followed the tether-release protocol during clinical research and induced a fall while a subject was engaged in a secondary 3D object selection task. The experiment employed a two-by-two design that evaluated two assistive techniques, i.e., video-see-through and auditory warning at two different timings, i.e., at fall onset and 500ms prior to fall onset. The data from 17 subjects showed that video-see-through triggered 500 ms before the onset of fall can effectively help users recover from falls. Surprisingly, video-see-through at fall onset has a significant negative impact on balance recovery and produces similar results to those of the baseline condition (no intervention).

Index Terms—VR, Fall, Balance

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1 INTRODUCTION

ROOM-SCALE virtual reality (VR) enables users to navigate a virtual environment by physically walking. Previous studies [1], [2] showed that the active usage of a user's body significantly improves the level of comfort and subjective presence in an immersive environment. However, the freedom of movement also magnifies the potential hazards related to falls caused by the disparity between the physical environment and the virtual environment. The consequences of a fall can be severe when a user is wearing a head-mounted display (HMD). A HMD obscures the vision of user's and prevents normal reactions, such as grasping external supports or avoiding nearby obstacles. An immersive virtual environment may also cause conflicts among sensory systems, e.g., an incongruency between the proprioceptive system and the vestibular system, which reduces a users capability of regaining stability after a loss of balance [3], [4]. Since room-scale VR is becoming a mainstream setup, evaluating potential balance recovery techniques and protecting users from accidental falls are important.

Few studies from the VR community have investigated balance recovery when a user is engaging in VR while wearing an HMD. Most related studies have focused on preventing potential falls caused by pedestrian collisions during eye-busy mobile interaction [5], [6] or avoiding accidental physical collision with surrounding objects [7]. Nevertheless, in health and medical research, fall prevention and recovery for the aging population have been an important research field [8], [9]. A significant amount of research was devoted to understanding the relationship between stepping responses and the severity of falls [10], [11], [12] and evaluating training procedures that help people to better react to falls [13], [14], [15]. This paper presents an interdisciplinary effort that evaluates balance recovery techniques for users who are wearing HMDs based on a revised lean-and-release protocol [16] with hardware built from off-the-shelf components and the tracking system of a commercial mass market VR headset HTC Vive.

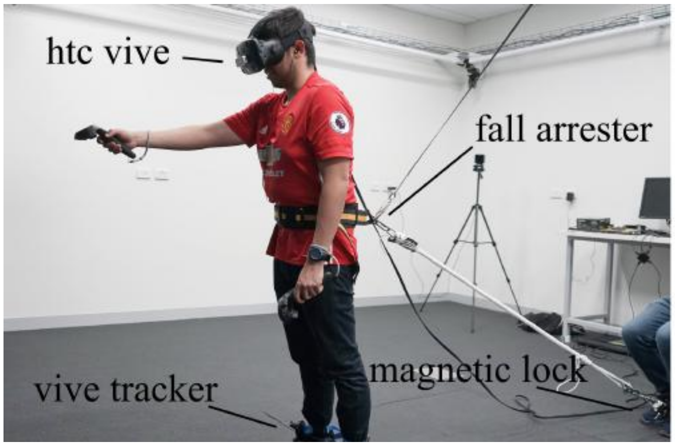

Fig. 1. Our experiment setup, which follows the tether-release protocol.

1.1 Balance Recovery in VR

With the assumption that the onset of a fall was given, we conducted an experiment to evaluate two balance recovery

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techniques, i.e., video-see-through and auditory warning at two timings, i.e., at fall onset and 500 ms before fall onset. We chose these two techniques because they do not require additional pieces of apparatus and are computationally feasible in a wide range of VR systems, from high-end systems, such as HTC Vive, to mobile-based solutions, such as Google Daydream. The experiment induced forward loss of balance using a tether-release protocol (Fig. 1), which has been applied in clinical fall prevention research [10], [17]. During the experiment, the subject was engaged in a secondary 3D object selection task using the Vive 3D controller. Forward loss of balance was induced by releasing the tether from a magnetic lock that was controlled by a solid-state relay. Following previous clinical trials using tether-release protocol [11], [16], we chose three measurements that can be readily obtained from the Vive tracking system, i.e., stepping strategies, step length, and step initiation time. We aimed to only use information provided by the HTC Vive's sensors and hoped that the proposed protocol can be reproduced outside a laboratory environment. The experiment examines three main hypothesis:

H1: Both video-see-through and auditory warning will increase the performance of balance recovery compared with the baseline condition of no intervention.
H2: A main effect of intervention timing exists.
H3: The video-see-through technique will yield the best performance.

Our main aim of this interdisciplinary collaboration was to establish an experimental protocol that can evaluate balance recovery techniques that may prove useful in assessing the effects of interventions aimed at improving balance. The proposed experimental setup used off-the-shelf components, and recovery methods that can be measured with most VR systems. We hope that this paper will draw attention to the safety issues during VR use and motivate additional research on the development of innovative balance-recovery methods.

2 RELATED RESEARCH

2.1 Loss of Balance in VR

When wearing a VR HMD, users are isolated from the real world, and accidental collisions with physical objects in the surrounding physical environment are not uncommon. Mismatches between the real world and virtual world produce behaviors that cause a loss of balance, such as colliding into physical objects that are invisible in the virtual world, leaning the body weight onto a virtual object that is nonexistent in the real world, or tripping over the cables of the VR system.

One way to eliminate this mismatch is to bring physical objects into the virtual environment, while minimizing the disruption to a subjects senses. Some researchers refer to this approach as *augmented virtuality*, in which virtual reality is enhanced with parts of the physical world, while grounding the experience in the virtual world. Budhiraja et al. [7] explored the design space of blending a physical nature scene into the virtual world to balance the ease of immersion and the ease of interaction. For example, bringing the physical nature scene into the virtual office window [18] or using video feed for virtual video conferencing [19]. Other studies eliminate the mismatch by *matching real world physical objects to the virtual environment*. Snake Charmer [20] brought physicality to the virtual environment via a robotic arm that holds physical objects that match the virtual presentation. TurkDeck [21] and Sparse Haptic Proxy [22] projects reproduce the haptic sensation with physical props.

Loss of balance in VR is sometimes internally triggered. Vection [3], which is an illusory sensation of the movement of the body induced by certain visual field movement patterns, is a notable example. A loss of balance often occurs when a user attempts to overly accommodate the illusory self-motion with dramatic physical body motion. Multiple online videos show users who lose their balance and even fall from a chair during a virtual roller coaster experience. Some intense VR experiences, such as virtual plank walking, may cause high levels of anxiety and stress, which hinder a user's capability of maintaining posture stability and may cause a loss of balance or even falls [23], [24].

2.2 Fall Prevention and Balance Recovery

The recovery techniques and the experiment design in this paper were inspired by research in the areas of balance, gait, and falls in older people. Fall prevention in older adults has received significant attention [25], [26] because falls are the leading cause of serious injuries in this population [27]. In addition to the traditional exercise programs [9], practitioners and researchers also leverage emerging technologies for fall prevention and fall risk assessment. For example, the iStoppFalls system [14] demonstrated how information and communication technology support can be integrated into the daily life of older adults. Research by Mirelman et al. [8] suggested that combining traditional treadmill training and a virtual training environment on a display in front of the treadmill reduced fall rates of older adults at high risk for falls.

Balance recovery is another important research topic that aims to understand the relationship between postural control and attentional demands [28]. Researchers have developed different paradigms to induce a loss of balance for subjects in a lab setup. Common paradigms involve a single leg stand [29], [30], artificial slipping tiles [31], changing the level of stability of the walking surface [30], and a tether-release protocol [11], [16]. Our experiment protocol was based on a tether-release cable system because this protocol simulates forward falls, which resemble falls in VR caused by tripping over obstacles or shifting weight onto nonexistent objects, and it has the potential to be custom-built with off-the-shelf components.

3 EXPERIMENT

Based on experiment protocols used in fall prevention studies [10], [11], [17], we conducted an experiment that simulated an unexpected loss of balance while users were immersed in a virtual environment through wearing a head-mounted display. We also conducted a user study that evaluated two balance-recovery techniques that were triggered at different times during an unexpected fall.

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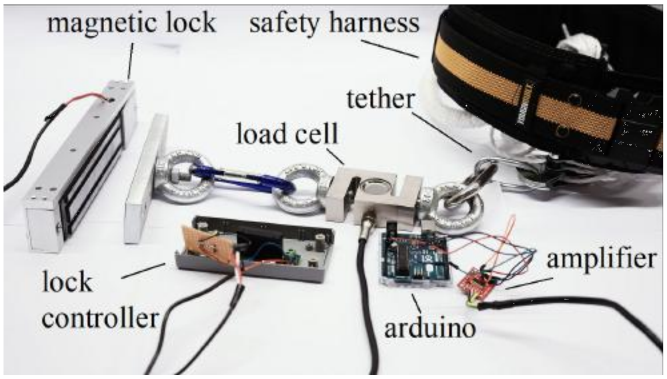

Fig. 2. Components of the tether-release mechanism.

3.1 Participants

We recruited 20 adults, whose ages ranged from 20 to 35 (mean = 25.38, variance = 10.23), of which 3 were female. All subjects were reimbursed 20 Australian Dollars for their time.

The key inclusion criteria for the users were fluency in the English language and the absence of major cognitive impairments. The key exclusion criteria for the users were inability to understand instructions, unstable health conditions, being blind or color blind, having any cognitive impairments, inability to walk independently, inability to step unassisted and the person being pregnant. This study received approval from the Institutes Human Research Ethics Committee. The data from 3 of the 20 recruited subjects (0 females) were discarded due to tracker malfunction, which produced incomplete or inaccurate data.

3.2 Experiment Apparatus

The experiment simulated a forward loss of balance and followed the tether-release protocol [17]. The subject was initially held in a static forward leaning position by a tether attached to a waist belt (Fig. 1). The subject was instructed to lean further until the load cell read a tension force of 20% of the subjects body weight. Forward falls were induced by releasing the tether.

Fig. 2 shows the components that were used to build the tether-release system. A Single Door 12 V Electric Magnetic Electromagnetic Lock of 280 kg, which was controlled by the Numato Labs Channel USB Solid State Relay Module, was connected by a serial port to the virtual scenario and served as the magnetic lock. A 0 – 300 kg S Type High-Precision Load Cell Scale Weighting Sensor served as the load cell. This load cell is positioned between the lock and the tether to record the tension force induced by forward leaning. To obtain measurable data from the load cell, the Sparkfuns Load Cell Amplifier HX711 was employed. An Arduino UNO R3 micro controller was used to convert the data from the amplifier and send it to the virtual scenario via a USB serial port. The virtual scenario was built using the Unity 3D engine. Our VR HMD was HTC Vive and a pair of Vive Trackers were attached to the subjects ankles (Fig. 1). A ceiling-mounted fall arresting harness was utilized as a security measure (Fig. 1).

3.3 Balance Recovery Techniques

The experiment employed a 2-by-2 design with two independent variables: *techniques* (video-see-through and auditory warning) and *timing* (fall onset and 500 ms before fall onset).

We chose *video-see-through* and *auditory warning* as the target balance recovery stimuli. Auditory warning has been extensively utilized in previous balance/postural control research ([32], [33], [25]). We assumed that the video-see-through approach will enable users to regain awareness of the surrounding physical environment to regain balance and avoid a fall. Note that other balance recovery techniques, such as merging the 3D reconstructed real-world surroundings into the virtual world [7] or displaying the posture of users in the virtual world, are also plausible. However, these techniques require substantial computation and/or additional hardware components. Thus, we focused on the current techniques, which are generic and can be implemented in PC-based, phone-based, and stand-alone VR platforms.

Video-see-through and *auditory warning* techniques were deployed at two different times: 500 ms before fall onset and during fall offset. When deciding the time to react, we selected a number that provides ample time for the subject to process the visual and auditory information and react accordingly once a fall occurs. Previous research by Lord et al. [34] indicated that a reactive behavior requires approximately 300 ms, while a decision-based behavior requires approximately 700 ms. Mochizuki, et al. [33] suggested that cortical activities were recorded 950 ms before the self-initiated fall in an tether-release experiment. Ng et al. [35] determined that the average finger response time to a visual stimulus is approximately 500 ms. Based on these previous findings, we chose 500 ms before fall onset as the time to intervene.

3.3.1 Implementation Details

We implemented the video-see-through technique using the front-facing camera on HTC Vive. The cameras frame rate was set to 60 Hz, and the rendering mode was set to undistorted to correct the camera lens distortion. To avoid the delay of the camera activation, the camera continuously streamed the video content as a video texture onto a 3D quad that was only visible when the video-see-through method was employed. The initial size of the quad was the default size set by the Steam VR library. Since we discovered that the size was too small to help the subject in any way, we doubled the size of the quad to create an illusion of a window to the outside world to users. After some informal pilot studies with subjects, we determined that this approach was not helpful. We attempted to make the quad sufficiently large to fully occupy the 110 FOV of the HTC Vive headset. Because a typical person has approximately 114 degrees of FOV, we decided that attempting to achieve the 110 degrees of FOV of HTC Vive for the video-see-through will produce a similar experience of observing the real world. We made the quad increasingly larger until it fully occupied a subjects vision. To achieve a more natural effect, we made the quad follow the subject’s view, which gave the subject the feeling that she was wearing glasses to view the outside world.

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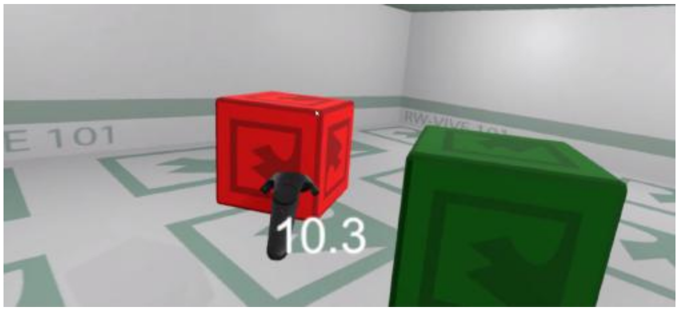

Fig. 3. Secondary 3D object selection task.

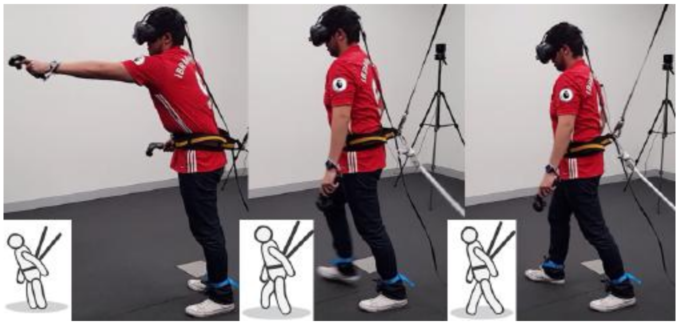

Fig. 4. Simplistic representation of body movements when executing Single Step Strategy.

Throughout a session, the auditory warning technique played a one-second standard neutral notification sound to the subject who wore a pair of headphones. The neutral notification sound is the only sound effect in the experiment

3.4 Experiment Protocol

The experiment employed a within-subjects design with five design combinations: *video-see-through at fall onset, auditory warning at fall onset, video-see-through at 500 ms pre-fall, auditory warning at 500 ms pre-fall* and a baseline condition with no intervention. Ten trials were performed for each condition, for a total of 50 trials to complete the experiment. The length of an experiment session was approximately 30 minutes.

In the introduction session, the experiment protocol was explained to the subjects, and then their weight was registered in the system. After putting on the HTC VIVE, Vive trackers, safety harness and fall arrester, each subject performed 5 test trials to become acquainted with the virtual environment and experience each technique once.

During an experiment session, at the beginning of each trial, the subjects were instructed to stand on a fixed position and then lean forward, while the reminder of the body segments were aligned in a single plane [36]. When the load cell registered a tension force of 20% of their weight, a secondary dummy object selection task in VR (Fig. 3) started. Subjects were instructed to reach to one of the three cubes in front of them as soon as the cube changed color. This secondary task was designed to keep the subject engaged with the virtual environment. After the secondary task started, the tether was released at a random time between 5 and 10 seconds, and the subject's balance response was recorded, which ended the trial. At the end of the experiment, a questionnaire was given to the subjects, which enabled them to rate each technique on a Likert scale from 1 (the technique was not useful) to 5 (the technique was very useful). Later, the subjects answered an open-ended interview that enquired about how immersed the subject felt in the experiment, how disruptive the balance recovery methods were and whether they preferred no intervention in favor of a seamless simulation.

Note that the threshold value of the tether tension affected the performance of the balance recovery [11]. The subject had to lean forward more to reach a larger tether tension threshold. The larger the leaning angle was, the more difficult it was for the participant to recover her balance. Previous studies [11], [37] suggested that a threshold value above 25% body weight would cause all participants to rely only on the multiple-step strategy for balance recovery. To include a wider spectrum of fall recovery strategies, our experiment adapted a 20% body weight threshold value. In our experiment, the average leaning angle to achieve the 20% body weight tether tension was approximately 15 degree, which concurred with previous observations by Barret et al. [38]. We also observed that this is a reasonable leaning angle that neither induces a considerable fear of falling nor breaks the sense of immersion in VR. To ensure all participants had a similar leaning angle, the tether was only released when the tether tension was within the range of 20% to 25% of bodyweight, which translated to a leaning angle of 13.5 ± 2.0 degrees [38].

4 MEASUREMENTS AND DATA PROCESSING

4.1 Measurements for the Tether-release Protocol

The tether-release protocol has a set of well-defined measurements [11], [16], including stepping strategies, margin of stability, sagittal plane angular position, and spatio-temporal variables such as stepping length and toe-off time. However, many of these measurements require extra apparatus such as motion tracking system and force plate. We intent to make our experiment protocol reproducible by researchers in the VR community, thus we use only the data stream from the native HTC Vive tracking system and a off-the-shelf web camera. This setup resulted in three major measurements: *stepping strategy, step length, and step initiation time.*

4.1.1 *Stepping Strategy*

We define three stepping strategies: *no-step, single-step, and multiple-steps* [11]. The *no-step* strategy is considered to be the best strategy because it exhibits the least body movement to recover balance. When adopting the *no-step* strategy, the subject recovers from a loss of balance by keeping her feet in place. The *single-step* strategy is the most common strategy; the subject recovers balance by taking one step (Fig. 4). The *multiple-steps* strategy is less ideal, often indicating a significant shift in the center of mass and instability of a subject and requiring more than one step to recover balance. Fig. 5 illustrates a typical multiple-stepping process, in which the first step of the subject is inadequate for stabilizing the shift of the center of mass and additional steps are required to regain balance.

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Fig. 5. Simplistic representation of body movements when executing Multiple Steps Strategy.

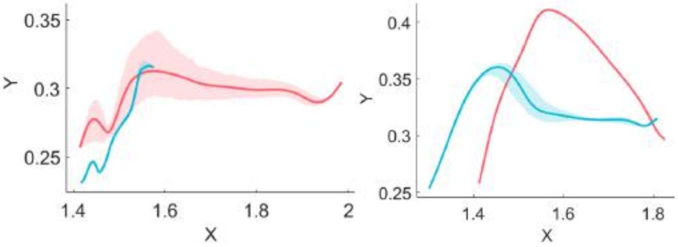

Fig. 6. Left: plot of the single-step feet movement. Right: plot of the multiple-steps feet movement. The bands on the plot represent 95% of confidence interval.

4.1.2 Step Length

The step length is estimated using the 3D position of the Vive trackers that are bound to a subjects leg. For each trial, the 3D position of the tracker on the first stepping leg is ustilized. In each trial, we identify time t, when the tracker has the largest displacement from its position at the onset of the trial. We average the 3D positions in the range of t 0.25 s to t + 0.25 s. A smaller step length for the first reaction step is generally considered to be a better reaction toward an unexpected fall [16]. A smaller step may be taken if a person is not capable of taking larger steps. However, this outcome is less likely for the healthy and young participants in this experiment.

For the trials in which a subject adopts the multiple-steps strategy, we define the step length as the displacement of the first reaction step only, as noted in previous studies [10], [16]. We did not accumulate the step length of all steps because the fall arrester (Fig. 1) usually disrupts a users motion after the first step.

4.1.3 Step-Initiation Time

The step-initiation time is defined as the amount of time required from the moment a subject initiates their response to the onset of a fall [10], [37]. A shorter step-initiation time indicates a better reaction performance toward an unexpected fall. In other words, Step initiation is the measurement of how early or how late a foot starts moving after the onset of a fall. The earlier the foot starts moving, the better prepared is a user toward the fall.

4.2 Data Processing

We annotated the subjects stepping strategies for each trial by examining the 20 hours of recorded videos of all experiment sessions. The annotations were corroborated by the trajectories of the foot movements. For the single-step strategy, we looked for plots in which only one of the feet moved arcwise and the other foot remained stationary (Fig. 6 left). For the multiple-steps strategy, we looked for plots in which both feet moved arcwise (Fig. 6 right).

Among the 20 subjects, data from 1 subject were removed due to inaccurate signal tracking during the experiment. Data from 2 subjects were removed due to light base movement during the experiment. Trials with a step length larger than 1.5 standard deviation are treated as outliers. Trials with distinct data defects, such as signal dropout or abnormal fluctuation, were also removed. Of 850 trials, 19 trials were removed in this process.

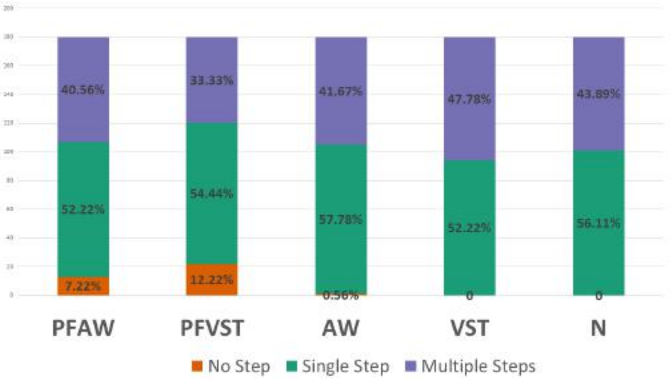

Fig. 7. Bar charts that represent the distribution of no-step, single-step, and multiple-steps for the 5 mitigation methods.

5 RESULTS

This section reports the results using the following abbreviations: *AW* for auditory warning, *VST* for video-see-through, *PFAW* for pre-fall audio warning, *PFVST* for pre-fall video-see-through, and *N* for the baseline condition with no intervention. For the stepping strategies, we use NS for No-Step, SS for Single-Step and MS for Multiple-Steps. For brevity, we refer to trials in which subjects adapted the single-step strategy as SS trials; the same naming convention applies to the MS trials and N Trials. For all the plots in the results section, the bands displayed represent 95% of confidence interval.

5.1 Stepping Strategy

The bar chart in Fig. 7 shows the percentage of the resulting stepping strategies for all 5 mitigation methods. The SS strategy was the most predominantly employed strategy across the conditions; the MS strategy was the second most prevalent strategy. *PFAW* and *PFVST* conditions induced some use of the NS strategy, while *VST* and *N* conditions did not induce any use of the NS strategy. The no-step and single-step recovery strategies yield more desirable reactions to an unexpected fall [12]. These results suggest that *PFVST* may enable a better recovery, while *VST* appears similar to the baseline condition.

5.2 Overall Analysis

Fig. 8 shows the first step length for all five conditions. Fig. 9 shows a box plot of the step length for each condition. For the MS trials, only the first step length is presented. The step length for each condition are *PFAW*

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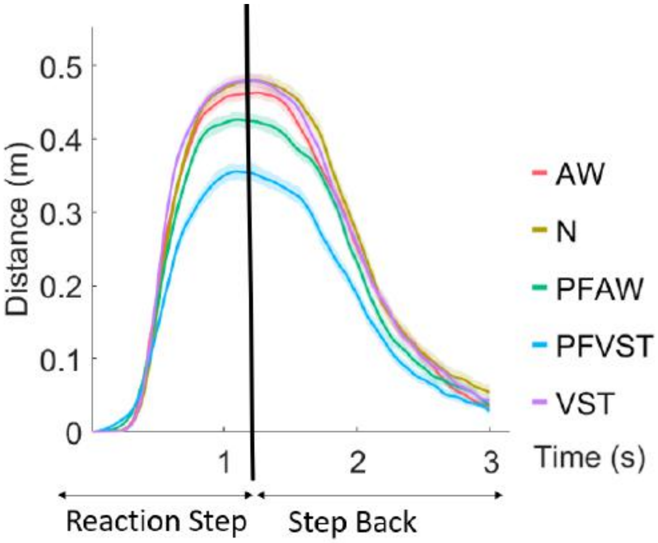

Fig. 8. Movement of the first reaction step over time for all trials.

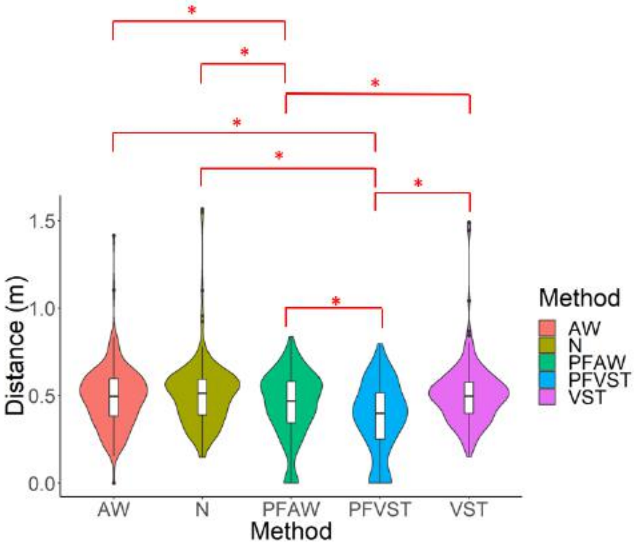

Fig. 9. Box plot of the step length (m) of all trials. * means significant difference (p <0.05).

$(\mu = 0.4459, \sigma = 0.1916), PFVST(\mu = 0.3742, \sigma = 0.2026), AW(\mu = 0.4897, \sigma = 0.17504), VST(\mu = 0.5063, \sigma = 0.1769), and N(\mu = 0.50908, \sigma = 0.19108)$.

A multiple linear regression analysis showed that the *timing* variable $(Beta = -0.04375, p = 0.03252)$ and the *timing * technique* interaction $(Beta = -0.08827, p = 0.00238)$ had a significant effect on the step length. The total model fit was R-squared = 0.06542.

A Kolmogorov-Smirnov (with Lilliefors Significance Correction) test and a Shapiro-Wilk test for normality were performed to test the step length for normality. The analysis showed that the data do not follow a normal distribution (p <0.05 for all 5 methodologies). A permutation test of independence showed there was a difference in at least two of the methodologies $(maxT = 6.7289, p{-}value = 6.97e{-}11)$. A pairwise permutation test was used as a post hoc test to identify which combination presented a difference. This analysis indicated that PFVST had a shorter step length than the other techniques and was significantly different compared with all techniques: with *PFAW* $(\pm 0.0717m, p = 0.0011)$, with *VST* $(\pm 0.132m, p = 2.212e - 9)$, with *AW* $(\pm 0.1154m, p = 9.89e - 8)$, and with *N* $(\pm 0.1348m, p = 4.091e - 9)$. The second shortest step length was produced by *PFAW*, which produced a significantly different step length compared with *VST* $(\pm 0.06m, p = 0.003132)$, compared with *AW* $(\pm 0.09, p = 0.03)$ and compared with *N* $(\pm 0.063m, p = 0.003132)$.

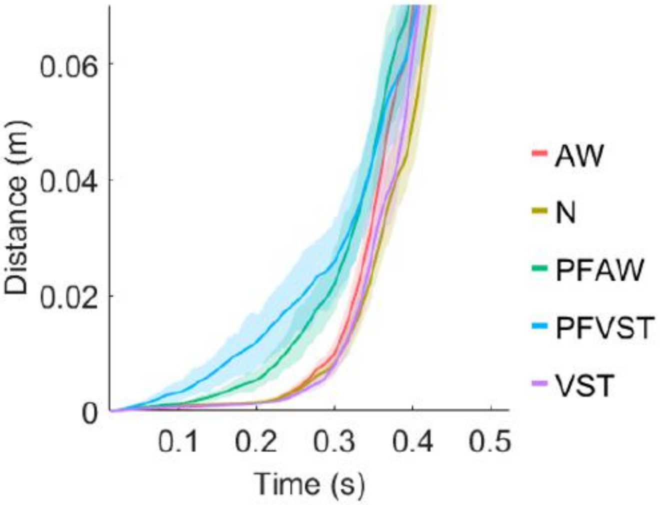

Fig. 10. Step Initiation for all trials. *PFVST* and *PFAW* are the methods that present a faster step Initiation.

Both the *PFAW* method and the *PFVST* method outperformed the baseline regarding the step length and the step initiation time. The *PFVST* method exhibits the best performance. Conversely, the measurements of *AW* and *VST* do not show significant difference against the baseline condition.

Fig. 10 shows the step initiation timing for each condition. An earlier notification of the fall onset causes in an earlier step initiation for the *PFVST* and *PFAW* conditions. As suggested in previous studies [10], [16], an early step initiation is optimal for improved recovery from an unexpected fall, which corroborates the result of the step length.

5.3 Trials with Single Step Strategy

This subsection reports the measurements for SS trials. Fig. 11 shows the averaged foot movement distance after the fall onset for SS trials. Fig. 12 shows the box plot for the averaged step length for SS trials. The step length for each condition are *PFAW* $(\mu = 0.4767, \sigma = 0.1532), PFVST(\mu = 0.4222, \sigma = 0.1558), AW(\mu = 0.4879, \sigma = 0.1278), VST(\mu = 0.4966, \sigma = 0.1555), and N(\mu = 0.5059, \sigma = 0.1821)$.

A multiple linear regression analysis revealed that the *timing* variable $(Beta = -0.04266, p = 0.00775)$ and the *timing * technique* interaction $(Beta = -0.0631, p = 0.0473)$ had a significant effect on the step length. The total model fit was R-squared = 0.03754.

A Kolmogorov-Smirnov (with Lilliefors Significance correction) test and a Shapiro-Wilk test for normality were

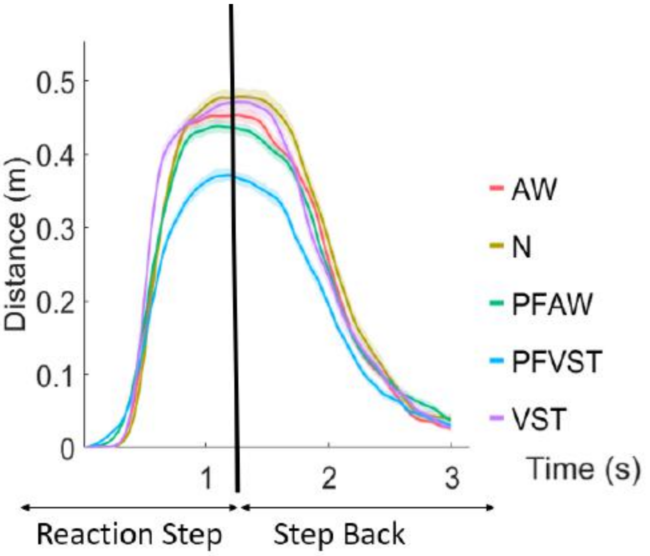

Fig. 11. Movement of the reaction step in single-step trials.

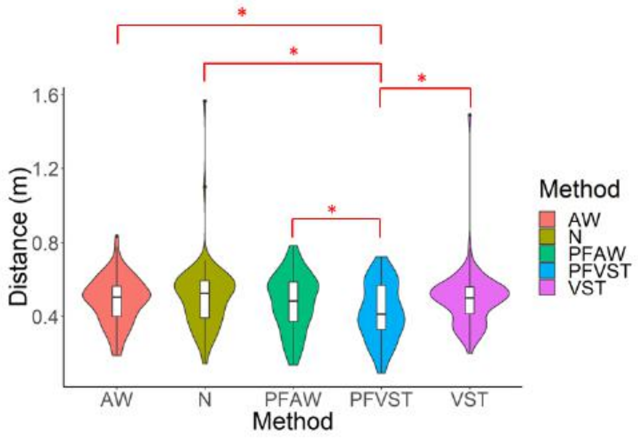

Fig. 12. Box plot of the step length for trial using single-step strategy.

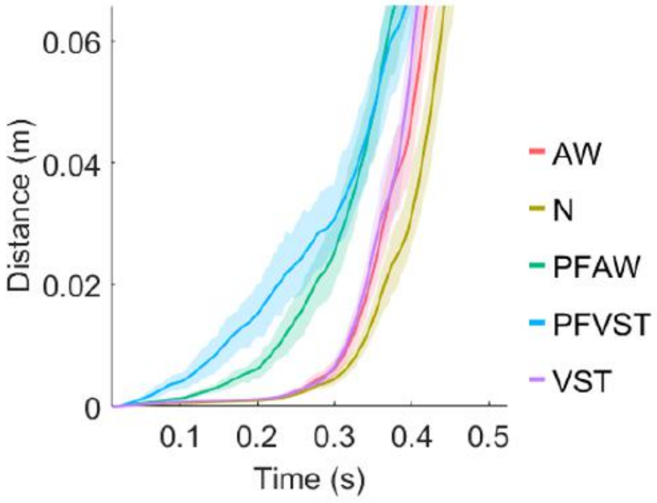

Fig. 13. Step initiation for trials using single-step strategy. *PFVST* and *PFAW* present the better step initiation.

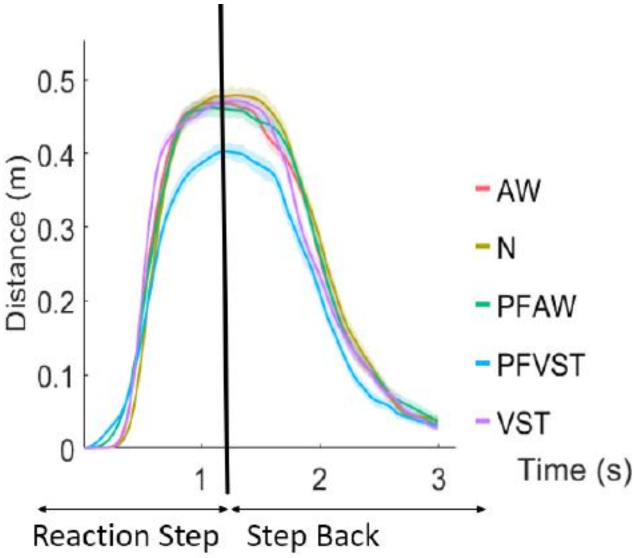

Fig. 14. Movement of the first reaction step in multiple-steps trials.

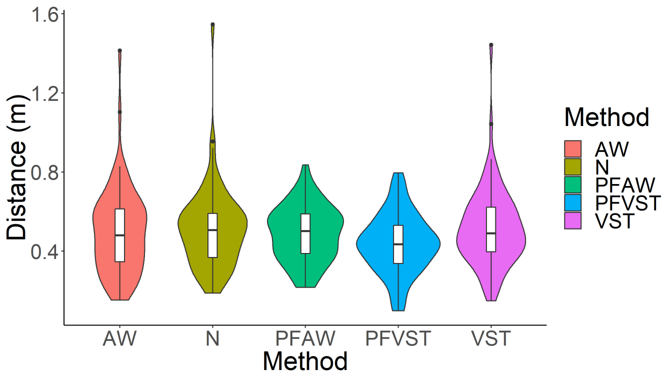

Fig. 15. Box plot for the step distance of trials using multiple-steps strategy.

performed to test the SS step length for normality. The analysis showed how only *PFVST* followed a normal distribution in the KS test, and how *AW*, *PFAW*, and *PFVST* follow a normal distribution in the SW test ($p > 0.05$). A permutation test of independence showed there was a difference among at least two of the methodologies $(maxT = 3.7218, p - value = 0.001024)$. A pairwise permutation test was used as a post hoc test to identify which combination presented a difference. The test showed a significant difference between *PFVST* and the rest of the methodologies: with *PFAW* ($p = 0.02273$), with *VST* ($p = 0.002137$), with *AW* ($p = 0.00237$), and with *N* ($p = 0.001317$).

Fig. 13 shows the step-initiation times for the SS trials. Similar to the results shown in Fig. 10, the *PFAW* and *PFVST* techniques exhibit an earlier step initiation.

5.4 Trials with Multiple-Steps Strategy

This subsection reports the measurements for the MS trials. Fig. 14 shows the average foot movement distance of the first reaction step among multiple steps after fall onset for the MS trials. Fig. 15 shows a box plot for the step length of the first reaction step for each condition. The step length for each condition is *PFAW*

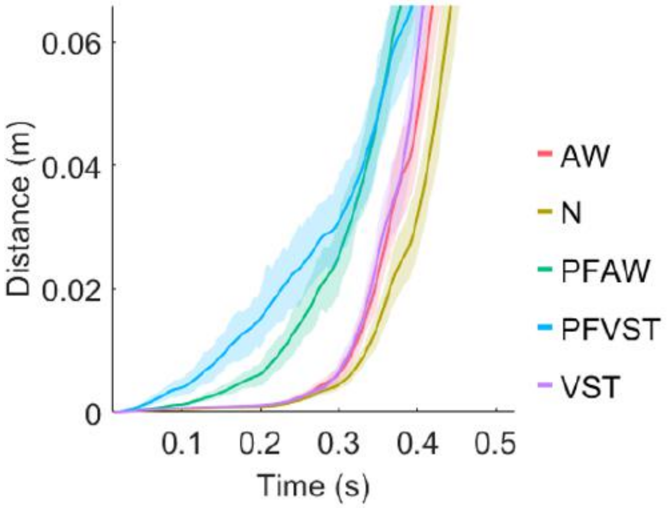

Fig. 16. Step initiation for trials using multiple-steps strategy.

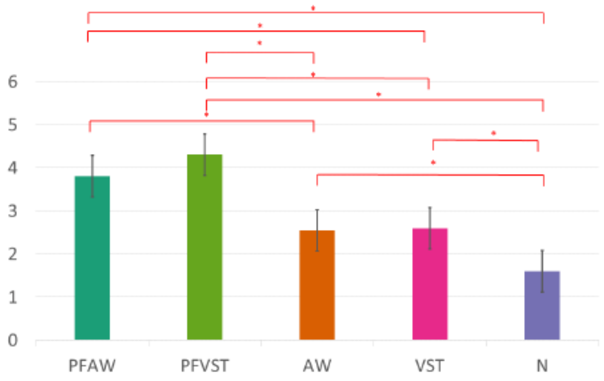

Fig. 17. User ratings towards the assistive techniques with 1-5 Likert scales.

$(\mu = 0.4909, \sigma = 0.1401), PFVST(\mu = 0.4382, \sigma = 0.1512), AW(\mu = 0.4985, \sigma = 0.2152), VST(\mu = 0.5163, \sigma = 0.1973), and N(\mu = 0.5129, \sigma = 0.228).$

A multiple linear regression analysis reported that the *timing* and *technique* variables do not have a significant effect on the step length both isolated or combined. The total model fit was R-squared = 0.02273. A Kolmogorov-Smirnov (with Lilliefors Significance correction)test and a Shapiro-Wilk test for normality were performed to test the MS step length for normality. The analysis indicated that only *N* does not follow a normal distribution for the KS test and *PFAW*, and *PFVST* follow a normal distribution for the SW test $(p > 0.05)$. A permutation test of independence was conducted to identify any differences among the methodologies. The test revealed no differences among at least two of the methodologies $(maxT = 2.4618, p-value = 0.6422)$.

Fig. 16 shows the step-initiation times for the MS trials. Unlike the plot for the SS trials (Fig. 13), the *PFAW* and *PFVST* conditions do not exhibit a distinct advantage over other conditions. Because subjects were less prepared for the fall, which was evidenced using the multiple-steps strategy, and thus, could not take full advantage of pre-fall stimuli.

5.5 User Ratings

Fig. 17 shows the results of the questionnaire (the questionnaire can be found in the appendix) about subjects preferences for the assistive techniques for regaining balance after fall onset. The results suggest that subjects preferred pre-fall interventions, i.e., *PFVST* and *PFAW*, while baseline had the lowest rating. A permutation test was performed to identify any differences among any of the conditions. The results show how *AW* and *VST* are statistically equivalent, and how *PFAW* and *PFVST* are also statistically equivalent. The remaining combinations were significantly different.

6 DISCUSSION

The results showed that our claims on *H2* were correct and that pre-fall interventions generally induce better performance. The *PFVST* and *PFAW* conditions more efficiently help users recover from a fall than the no intervention (baseline) condition. The *PFVST* condition produced the smallest step length, an earlier step initiation timing and the largest number of no-stepping trials. The result of questionnaire also suggested that users find PFVST and *PFAW* more useful than other conditions. The results provide preliminary evidence that an early intervention and re-exposing a user to the real world environment help the balance recovery process, although at the cost of disrupting the virtual experience before a fall actually happens.

For the SS trials, *PFVST* condition outperforms all other techniques, including the *PFAW*. We believe this is due to the sudden interruption in the simulation to display the visual input to assist balance recovery compared with the auditory input.

Both *H1* and *H3* were only partially correct. Contrary to our expectations, the *AW* and *VST* conditions, which occur at fall onset, did not cause significant improvement compared with baseline. Only the pre-fall interventions increased the performance of balance recovery. The *VST* condition even induced a larger average stepping distance and a larger step initiation time. Our *H3* was only partially correct because *PFVST* proved to be the best method among the pre-fall methodologies.

We suspect that *VST* and *AW*, in providing additional sensory information and requiring multisensory integration at fall onset, may have disrupted the subjects mental process of regaining balance. Balance is achieved by integrating sensory inputs, such as visual, proprioception, haptic, and the vestibular system [33], [39]. When a sensory input is missing, balance is maintained by the integration of the remaining sensory inputs. In our experiment, the vision of a subject is blocked by the headset; thus, she mainly relied on the proprioception and the vestibular system for balance control. The sudden introduction of visual (*VST*) or auditory (*AW*) input at fall onset forced an untimely sensory integration process and further disrupted the balance, at least for a short period of time. *PFVST* and *PFAW* conditions caused better performance because the sensory integration processes were completed before fall onset and the subjects are better prepared for a fall.

This result suggests that both the type and the timing of the sensory inputs affect how users recover from a loss of balance. Further investigation of the different timings

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associated with integration of different sensory inputs for balance control is suggested.

6.1 Disruption of Immersion

According to the post hoc interview, all subjects seem to be fully engaged in the secondary task of object selection in VR. We did not observe significant behavioral changes from 5 to 10 s, when the tether was randomly released. Eight subjects commented that all intervention techniques disrupted their sense of presence in the virtual environment. One subject even favored the baseline of no intervention as the best method because she disliked being interrupted in the virtual environment, even when facing the fall hazard. Ten subjects preferred the auditory warning because it was less disruptive to the VR experience. However, five subjects commented that they completely disengaged from the object selection task and were fully preparing for the upcoming fall upon hearing the auditory warning.

Finding optimal combinations of intervention timing and stimuli that increase the chance of a successful recovery from a fall, while minimizing the disruption of immersion, is an important and challenging research topic. We believe an ideal system should consider a user's physical capability and personal preference to VR experience and adaptively assist the user at different phases of a fall, i.e., before onset, during onset, and after onset, with different techniques. We hope this paper can serve as the first step toward a reliable experiment protocol that is capable of efficiently exploring the design space of intervention timing and stimulus.

6.2 Effect of See-Through Video

Although *PFVST* yielded the best performance, the results do not provide direct evidence on how participants utilized the visuals of the surrounding environment in the process of balance recovery. In the post hoc interview, two participants specifically stated that the video stream enabled them to look down at their foot, giving them more confidence in their recovery from a fall. Five participants complained about the low resolution of the HTC Vive video and stated that they believed a higher quality video stream would make the video-see-through method more preferable. These responses seem to suggest that some users are aware of the see-through video content during the process of balance recovery. The use of an HMD with integrated eye-tracker is an interesting research topic to understand how the video feed affects the user behavior during balance recovery.

6.3 Learning Effect

A learning effect is observed in multiple subjects who initially employ a multistep strategy to regain balance and then evolving into a single-step strategy or a no-step strategy. Fig. 18 shows an accumulated stepping strategy usage. We observe a slight decrease in MS and an increase in NS toward the end of the experiment. The results suggested that, as the experiment progresses, subjects gradually became more efficient in regaining their balance when experiencing an unexpected fall. Our experiment protocol addressed this issue by counterbalancing the occurrence of the conditions for each subject.

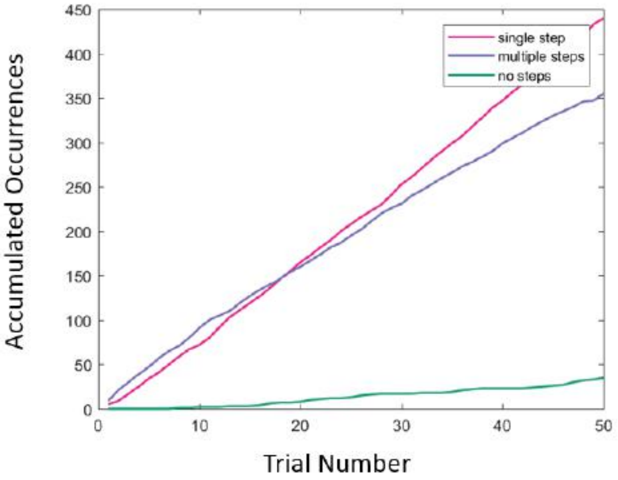

Fig. 18. Accumulated trial numbers for each stepping strategy.

Another possible interpretation of this result is that the subjects gradually shifted their attention toward the release of the tether during the object selection task. However, the data did not show a significant change in the reaction time of the object selection task and the current design of using a random release timing from 5 to 10 s is plausible.

7 FUTURE RESEARCH

We believe the design space of enhancing user safety when wearing an HMD is underexplored. The following sections outline potential research topics.

7.1 More Naturalistic Setting

We chose the tether-release protocol for our experiments because its setup has the precise control of fall onset and the measurements are well established. However, it has two major limitations: 1) it is constrained to forward falling (tripping) and 2) leaning forward is usually not a naturalistic posture for VR users.

There are many different experiment paradigms to induce a fall, e.g., a sliding tile on the floor [40], an unexpected obstacle [41] or a sudden force at the waist [42]. There are also subjective and objective measurements for evaluating the level of presence in VR [43], [44], [45]. We believe the findings described in the paper should be applicable in these different paradigms. However, we also expect the effective timing required for balance recovery might be quite different.

7.2 Detection and Prediction of Fall

The detection and prediction of a fall has been an important research problem. The marginal stability method [46] provides reliable prediction but requires the knowledge of the center of mass and the base of support. Previous research has achieved fall detection using accelerometers on the waist [4] and in a phone [47]. Tong et al. [48] proposed a fall prediction model based on a triaxial accelerometer in a belt.

Most VR HMDs have accelerometers embedded. However, our initial analysis on the collected head movement data found that most users naturally try to maintain the stability of their head, which greatly reduces the predictive power of the data. We believe a different sensor setup and a sophisticated data fusion algorithm are needed to achieve a reliable prediction of fall onset. Further investigation on how to achieve a more precise prediction of fall onset using different sensor combinations and different data fusion algorithms is needed for a safer VR experience.

7.3 Other Potential Techniques for Balance Recovery

In addition to the video-see-through and auditory warning techniques proposed in this paper, numerous techniques remain to be explored. For example, showing the full body posture to enhance the proprioception, using electrical muscle stimulation to navigate a user [18], [49], or even rendering inertia to counter a fall [50].

8 CONCLUSIONS

This paper identified the risk of loss of balance while users are wearing VR HMDs and proposed a modified tether-release protocol to evaluate different balance recovery methods. Following the proposed protocol, an experiment was presented that evaluated two balance recovery methods at two timings of intervention. Both balance recovery methods, i.e., video-see-through and auditory warning, at 500 ms prior to fall onset improved the performance of balance recovery. However, the results also suggested that intervention at fall onset may distract a user's attention and have a negative effect on the performance of balance recovery. Future developments of balance recovery methods in VR should carefully consider the variable of the timing of intervention to avoid confusion.

APPENDIX
END OF EXPERIMENT QUESTIONNAIRE

We would like to know some information regarding the last experiment.

Please select a number from 1 to 5 how useful where the mitigation methods user during the experiment(5meaning the method was really useful, 1 meaning the method was not useful at all).

- Sound notification before fall
- Sound notification during fall
- Camera display before fall
- Camera display during fall
- Nothing

Please describe how these techniques affected your level of immersion:

- Sound notification before fall
- Sound notification during fall
- Camera display before fall
- Camera display during fall
- Nothing

Please describe if any of these methods where helpful on regaining balance:

- Sound notification before fall
- Sound notification during fall
- Camera display before fall
- Camera display during fall
- Nothing

Where the timing of the camera and sound notification before the fall useful? Or do you consider the time should have been increased/decreased?

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