1. Introduction

Standing balance is essential for many activities of daily living (ADLs), and losses in balance (i.e. falls) are a significant public health concern. To prevent falls, individuals must control their center of mass (COM) location over the base of support (BOS) during both voluntary movements, and in response to external, destabilizing forces [1–3]. This form of postural control is deficient in a wide range of clinical populations, and is sub-served by multiple risk factors. These factors include issues relating to both sensory and motor systems, which combine to cause postural dysfunction [4,5]. To this extent, clinicians and researchers have been searching for decades to elucidate effective balance training protocols.

Exer-games, video games designed to improve overall health and body fitness, are a relatively new frontier in the field of physical medicine and rehabilitation. This approach to medicine utilizes virtual reality technology to create interventions that are easy to access, cost-effective, and engaging for the participant [6–8]. One of the most popular devices to be implemented in both clinical and research domains is the Nintendo Wii Fit. The Wii Fit debuted on December 1st, 2007 and consists of a Wii balance board (WBB) device that tracks body sway via center of pressure (COP) when stood upon. This information is input wirelessly to the Wii game console to control an avatar (called a Mii) during various mini-games.

A recent review by Goble et al. demonstrated that Wii Fit training is effective for improving overall balance in both healthy and clinical populations [9]. However, a main conclusion of this review was that study results to date have been largely clinical in nature, based on tests such as the Timed Up and Go, Berg Balance Scale, and Tinetti test [10–13]. Such tests, while popular, lack information regarding the specific mechanisms underlying balance control. In this way, there remains a paucity of information...
regarding what aspects of balance are actually improved following Wii Fit balance training.

One aspect of balance that has yet to be fully assessed with Wii Fit training is the ability to process convergent sensory information from the visual, vestibular, and somatosensory systems—known as sensory weighting. Advancements in technology over the past several decades, such as the NeuroCom Balance Manager, now allow for the contributions of various sensory feedback sources to be assessed during static stance. The Sensory Organization Test (SOT) is one particular assessment that measures a person’s ability to maintain quiet standing while sensory information is eliminated or made inaccurate. COP is analyzed in this test over various conditions that differ in terms of the accuracy of visual and somatosensory feedback provided. These sources of sensory information are manipulated via a moveable visual surround, a rotating force platform, blindfolding, or a combination of the aforementioned.

A second important mechanism that can be addressed using the Neurocom Balance Manager device is the ability to shift COM within the BOS, also known as limits of stability (LOS). In the LOS, the dynamic, motor component of balance control is measured via a person’s ability to shift their COM in various directions with the intent of reaching a maximum displacement. Previous work has shown that the LOS test is a reliable predictor of functional BOS. Functional BOS is the maximal distance an individual can voluntarily displace their COM over their BOS without losing balance. Establishment of a large functional BOS is important, as most injuries fall occur during dynamic ADLs [1,14].

In light of the above, the present study sought to determine whether sensory weighting and/or LOS mechanisms are impacted by a Wii Fit game-based intervention. To accomplish this, changes in SOT and LOS performance were assessed before and after 6-weeks of game-based training in healthy young adults. Young adults were studied for two reasons. First, younger adults are ideal for mechanistic work, as they are less likely to be confounded by comorbidity issues. Second, any positive changes that can be elicited in a younger population might be expected to be amplified in individuals with known balance impairments.

Due to the inherent need for sensory reweighting during Wii Fit gameplay, we hypothesized that SOT performance would improve, especially in the most difficult conditions where multiple sources of sensory feedback were compromised. Further, since gameplay on the Wii Fit requires rapid and controlled displacement of the COM towards the limits of functional BOS, it was expected that the time to initiate and execute COM displacements would decrease and that displacement of the COM would increase following training.

2. Methods

2.1. Participants

Forty young (age range = 18–35 years), healthy participants were recruited for the study. The American Heart Association/American College of Sports Medicine Health/Fitness Facility Preparticipation Questionnaire was utilized to determine each subject’s general health status. In addition, individuals with self-reported lower extremity injuries within the previous six months were excluded. Participants were conveniently placed into either a Wii Fit Balance Intervention (WFBI) or a Control (CON) group matched for mean age (WFBI = 23.4 ± 3.7 years; CON = 22.3 ± 2.0 years) and gender (12 men, 8 women). The CON group was offered the opportunity to participate in the training aspect of the study after serving as a CON. The local ethics committee approved the study and all participants gave written informed consent.

2.2. Balance testing setup and procedure

The NeuroCom Balance Manager (NeuroCom International Inc., Clackamas, Oregon, USA) was utilized to perform all balance testing. This device has a moveable force plate that measures COP as a proxy for body sway during standing and a moveable visual surround. Both the force plate and visual surround can be programmed to synchronize with the participant’s COP, known as sway-referenced motion. Sway-referencing of the force plate limits changes in ankle position during body sway by rotating at the axis of the ankles in the sagittal plane. This manipulation reduces important proprioceptive cues from the ankles during standing. Similarly, sway-referencing of the visual surround occurs in the sagittal plane, keeping the eyes a constant distance from the surround in front of the participant. This manipulation limits important visual depth cues from occurring during standing.

Prior to balance testing, participants were outfitted with a safety harness to prevent falls, which was secured to the top of the NeuroCom apparatus. All trials were performed in double stance, with a width that was standardized across participants. Once in the starting position, participants began balance testing by performing the SOT. The investigator instructed each subject to look straight ahead at all times, maintain normal posture, and remain as still as possible. Talking was not permitted during trials, and at the beginning of each trial, the investigator instructed the participant to either open or close their eyes. Trials were performed in a pseudo-randomized order.

For the SOT, six separate conditions, with three trials each, were performed that progressively challenged the participants’ ability to maintain upright stance by altering different sources of sensory feedback. Condition 1 was a baseline condition where all sources of sensory information were unperturbed. In condition 2, participants were asked to close their eyes in order to eliminate visual feedback. Condition 3 required participants to leave their eyes open, but with vision perturbed by activation of the moveable surround (i.e. surround sway-referencing). During condition 4 the eyes were open, but the force platform underneath the participants’ feet rotated around the frontal axis (i.e. force plate sway-referencing) to distort proprioceptive feedback. Condition 5 had two sensory challenges with vision eliminated through closing of the eyes and proprioception distorted by force plate sway-referencing. Lastly, condition 6 also had two of the sensory systems compromised as both vision and proprioception were perturbed via sway-referencing. Each trial lasted for 20 s, which began and ended via an audible tone projected from the NeuroCom controlling computer.

SOT Trials were scored using the NeuroCom SOT metric. This is calculated as follows:

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\text{SOT Score} = 100 \left[12.5 - \left| \theta(\text{A}) - \theta(\text{P}) \right| \right] / 12.5
\]

This equation assumes that the maximal AP COP displacement possible for individuals in normal stance is 12.5 \( \theta \max (\text{A}) \) is the maximum amount of COP displacement in the anterior direction that the participants traveled, with \( \theta \max (\text{P}) \) being the maximum in the posterior direction [15]. No participant lost balance during a trial.

Following SOT testing, participants were given a short break (~5 min) prior to performing the LOS test. For LOS testing the same stance described for the SOT was utilized, and a monitor on the visual surround was turned on. The monitor displayed an avatar that reflected participants’ COP location, as well as a center square and eight targets in different directions (45° apart). Participants were instructed to start each trial with their avatar in the center square, and shift their COP as quickly as possible towards the

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highlighted the target once an auditory signal was given. After reaching the target (or getting as close as possible), participants had to hold their maximal displacement until the end signal was given.

The LOS test consisted of eight trials, one for each of the directional targets. Trials lasted 8 s, and participants were required to have both feet firmly on the ground at all times. Participants completed the trials in a clockwise manner starting from the front-most target, per standard LOS testing protocol. Five variables were measured from the LOS test including: response time, COP movement velocity, maximal excursion, endpoint excursion and directional control. Response time was measured as the amount of time (in seconds) between the starting signal and the participant’s initial movement towards a target. Movement velocity was measured through average speed of COP in degrees/seconds. Maximal excursion was the furthest COP displacement occurring during each trial. Endpoint excursion was calculated by finding the initial movement displacement, as a percentage of the maximal excursion. Lastly, directional control measured the smoothness of the COP leaning towards the target by comparing movements towards the designated target vs. movements away from the target.[17] The pre- and post-intervention balance assessments were given six weeks apart for the CON group (±3 days) and within 3 days before and after the 6-week training intervention for the WFBi group.

2.3. Wii Fit intervention setup and procedure

The Wii Fit balance intervention was conducted using the Wii Fit bundle from Nintendo (Nintendo Co., Ltd., Kyoto, Japan). This consists of the Wii console, a ‘Wii-mote’ hand controller device, a WBB, and the Wii Fit Plus balance game disc. These components were interfaced with a large screen television (42 in.) located approximately 152.4 cm (5 ft) to the front of participants. During training the participants stood on the WBB with a safety railing surrounding them on three sides (front, left and right) to assist in the event of balance instability.

To start a training session, the television and console were turned on and the Wii Fit Plus program was loaded. From the main menu a training session was selected and one of seven different balance ‘mini-games’ was chosen. Games included table tilt, penguin slide, ski Slalom, tightrope, balance bubble, soccer heading and snowboarding. Each game involved movement of either the participant’s avatar on the screen, or some object in the gaming environment, via changes in COP measured by the WBB. A research assistant was present for all training sessions.

The intervention consisted of a total of 18 sessions conducted over a six-week period. Each week, WFBi participants completed 2 to 4 training sessions on the Wii Fit. Sessions were never more than four days apart, and each session lasted about 45 min, with a minimum of 30 ‘game-time’ minutes (calculated by a running total on the Wii Fit). Participants were required to play each game at least once a week. Participants progressed to harder modes of each game at an individual pace. This pace was determined through the balance exer-games’ star system that rates the participant’s performance on each individual game. Participants were only allowed to increase the difficulty setting once they performed at least three ‘professional’ scores (4 stars) to show a sustained ability to play the game at an optimal level.

2.4. Data analysis

An average SOT score was determined from the three trials conducted for each participant, on each of the six SOT conditions. In addition, a single score representing the mean of all eight targets was determined for each of the five LOS metrics. These data were then entered into multiple 2 (group) × 2 (time) mixed-design analyses of variance (ANOVAs) using the Statistical Package for the Social Sciences (SPSS Inc. Version 20.0, Chicago, IL, USA). Group (WFBI/CON) served as the between subject factor and TIME (Pre/Post) served as the repeated measure factor in each analysis. Significant interactions between TIME and GROUP were decomposed examining simple main effects with follow-up one-way ANOVAs. For these ANOVAs alpha level was adjusted using the Bonferroni correction (α/2 = 0.025). Partial eta-squared (η²) values were also calculated as a means of demonstrating treatment effect size.

3. Results

3.1. Game-based changes in sensory weighting

There were no significant main effects of group (WFBI vs CON), time (pre/post), or interactions between group and time, for conditions 1, 2, 3, 4, and 6 of the SOT. However, as shown in Fig. 1, there was a significant interaction (F(1, 38) = 5.90, p < 0.03, η² = 0.13) between group and time in condition 5 where both visual feedback was removed and force plate sway referencing was employed to disrupt proprioceptive information. Follow up one-way repeated measures ANOVAs to decompose this interaction revealed a significant increase in the average SOT score following balance training for the WFBi group on condition 5 (F(1, 19) = 18.74, p < 0.001, η² = 0.50). In contrast, there was no significant improvement over six weeks without training for the CON group in this condition (F(1, 19) = 0.23, p < 0.64, η² = 0.01).

3.2. Changes in dynamic balance following training

While there were no significant changes in directional control or maximal excursion seen in either group tested, there were significant interaction effects for endpoint excursion (F(1, 38) = 7.07, p < 0.02, η² = 0.16; Fig. 2a), movement velocity (F(1, 38) = 6.19, p < 0.02, η² = 0.14; Fig. 2b), and response time (F(1, 38) = 8.04, p < 0.008, η² = 0.18; Fig. 2c). Specifically, follow-up one-way repeated measures ANOVAs demonstrated that only the WFBi group had significantly improved endpoint excursion (WFBI: F(1, 19) = 17.44, p < 0.002, η² = 0.48; CON F(1, 19) = 0.21, p < 0.66, η² = 0.01), movement velocity (WFBI: F(1, 19) = 12.57, p < 0.003, η² = 0.40; CON F(1, 19) = 0.58, p < 0.46, η² = 0.03), and response time (WFBI F(1, 19) = 18.85, p < 0.001, η² = 0.50; CON F(1, 19) = 0.25, p < 0.62, η² = 0.01).

4. Discussion

Utilizing the SOT and LOS test of the NeuroCom Balance Manager, the objective of this study was to determine whether sensory weighting and/or dynamic BOS aspects of balance were subject to improvement following Wii Fit balance training. It was shown that 6 weeks of Wii Fit gameplay resulted in a statistically significant improvement of moderate effect size on condition 5 of
the SOT for only the WFBI group. These individuals also showed significant improvements of moderate effect sizes in response time, movement velocity, and endpoint excursion for the LOS test. There were no significant changes in balance ability for the CON group.

The enhanced performance of the WFBI group on condition 5 of the SOT suggests that individuals who play Wii Fit balance exergames improve their ability to weigh sensory information during upright stance. Specifically, when balance was dually challenged by removing both visual feedback and providing inaccurate proprioceptively input, WFBI participants incurred less COM displacement following training. This effect may reflect a shift to the remaining, accurate source of sensory information—that of the vestibular system. Indeed, a similar effect has been shown in other Wii Fit interventions and following virtual reality training [18–21].

Such a shift may implicate an improvement in vestibular function following Wii Fit training [21]. During game play the user was required to quickly displace COM in different directions, causing rapid changes in head position. It has been shown that this type of repetitive vestibular stimulation as part of a rehabilitation protocol can improve sensory signaling [22]. That said, it should be noted that a lack of change in conditions 1–4 of the SOT may be the consequence of a ceiling effect. Participant scores on these conditions were generally high, leaving little room for improvement with training. As for SOT condition 6, which was not subject to a ceiling effect, more variability was seen in performance. This may have precluded it from reaching statistical significance.

Based on LOS testing, this study found that Wii Fit training can decrease response time to auditory signals, increase average movement velocity in initial body sway displacement, and enhance the ability to reach functional BOS limits. These layered improvements are also well aligned with Wii Fit gameplay. Most of the games played are time-based, meaning that players are encouraged to make quick, ballistic movements of nominal accuracy in response to various auditory or visual cues. Such responses are similar to the constraint of an LOS test trial where participants move as fast as possible towards the highlighted targets following an auditory signal. Reaction time, in particular, has previously shown to be affected by a virtual reality training protocol with similar requirements for COM displacement [23].

Interestingly, during gameplay participants were never required to displace their COM to their functional BOS limits, which likely explains the lack of improvement in maximal excursion of the LOS test. Furthermore, most games played by the WFBI group only required general directional control to move the avatar appropriately, instead of requiring precise angles of movement. In this way, directional control was not frequently challenged, and this explains why only the metrics measured from the initial movement characteristics showed improvement. Each mechanism plays a crucial role in maintaining equilibrium when performing ADLs, when individuals most at risk for falling are most vulnerable [1,14].

The present findings also provide a justification for the use of similar balance interventions in individuals that have sensory weighting issues and/or difficulties with several aspects of dynamic balance control, particularly as findings were not only statistically significant but treatment effects were at minimum, moderate levels. This targeted approach can improve both the efficacy and efficiency of future fall risk intervention protocols.

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Conflict of interest statement

None of the authors has any conflict of interest to declare.

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