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Assessing Balance Loss and Stability Control in Older Adults Exposed to Gait Perturbations under Different Environmental Conditions: A Feasibility Study

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Abstract: This study investigated the feasibility of a perturbation-based balance protocol that incorporates a novel computer-controlled movable platform, the Surefooted Trainer, to induce losses of balance during overground walking under various environmental conditions. Twenty apparently healthy older adults (66.7 ± years old) participated in this study. The acceptability and safety of the perturbation-based balance protocol were assessed by tracking adherence, adverse events, and subjective physical and mental demands after the intervention. Additionally, biomechanical variables during perturbed and non-perturbed trials were analyzed and compared with behavioral outcomes. Overall, 95% of the participants completed the study. There were no serious or non-serious adverse events. The margin of stability and step length after perturbations were significantly lower during slip-perturbations in which the environmental conditions were more challenging. For trip-perturbation conditions, the maximum trunk angle was higher during the trials that resulted in losses of balance. We conclude that the Surefooted Trainer is an acceptable and valid device for an overground walking perturbation-based assessment and training protocol in older adults.

Keywords: balance control; perturbation-based balance training; older adults; reactive balance; sensory reweighted

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1. Introduction

Falls are a leading cause of mortality and morbidity in older adults and a significant public health issue [1]. Fall-related injuries, such as hip fractures [2] and head injuries [2,3], are among the most serious and common medical problems experienced by older adults and approximately 28% of community-dwelling older adults experience at least one fall each year [4]. Slips and trips during walking are the most common causes of falls among older adults [4], which represent failures to predictively (before the perturbation) or reactively (after the perturbation) respond to environmental challenges encountered in people's daily lives [5–7]. Therefore, it is essential to prepare the population at high risk of falling for situations where unexpected postural disturbances may occur.

It has been well described that perturbation-based balance training, defined as a task-specific intervention that aims to improve reactive balance control after destabilizing perturbations in a safe and controlled environmental [8], may reduce fall rates by 46–48% [8–11]. Thus, various methods have been developed to generate balance perturbations, including using a low-friction plate on a walkway [12], treadmill accelerations [11], motor-driven surface translations, and waist/ankle-cable pulls [13]. Although current perturbation-based balance overground systems may have high ecological validity by mimicking real-life hazards realistically, the perturbations usually occur at a fixed location, which leads to a loss of "unpredictability" [13,14], and could diminish the motor learning process expected to result from these training protocols [14]. On the other hand, motor-driven surface translation devices (such as a treadmill) offer advantages since they trigger slips and/or trips by sudden platform or belt accelerations, or changes of gait speed, which reduces the level of predictability observed in the overground training, helping to focus training on reactive components of balance control [15]. However, the transference from treadmill perturbation-based training to overground remain unclear. These issues have motivated different groups, dedicated to investigating balance through perturbation-based training, to evaluate new systems that combine the best of overground and treadmill setups, with the aim to develop novel training strategies able to train reactive balance, and with the potential to be implemented in clinical facilities [15].

Postural control involves both feedback (compensatory) and feedforward (anticipatory) responses [16] which are required to trigger compensatory strategies, such as modification of the base of support (BOS) and/or counter rotation of segments around the body's center of mass (COM) [17], to maintain postural stability during challenging conditions (e.g., perturbations) [18,19]. Error feedback information acquired from external perturbations is used to predictively adapt the locomotion to persisting or recurring perturbations in a feedforward manner [18,19]. However, such gait adaptation mechanisms may be less effective when participants are exposed to balance perturbations with high components of unpredictability [15], which is what usually happens before everyday falls. Along this line, and as opposed to self-controlled perturbations, external and unpredictable perturbations restrict an individual's ability to alter the perturbation intensity through proactive adaptation. Therefore, one might expect that recovering balance from externally controlled perturbations demands higher reliance on reactive adaptation via trunk control [20], and a rapid compensatory stepping response to achieve stability [21]. Thus, to maximize the acquisition of reactive balance control strategies (the final defense against falls in everyday life), training should regulate predictive behavior and include high components of unpredictability to perturbation-based training protocols [15,22].

Another important factor that affects gait stability and the reactive responses after experiencing a loss of balance is sensory reweighting, which has been defined as the process of adjusting the sensory contributions to integrate the environmental variables and maintain balance control [23]. It has been well described that balance control is achieved by the complex integration and coordination of multiple sensory systems, including the vestibular, visual, and proprioceptive systems [24,25]. Thus, Peterka showed the existence of sensory reweighting by demonstrating that quantitative estimates of sensory weights changed depending on the availability of sensory information from visual or proprioceptive systems, and depending on the amplitude of perturbations provided by visual surroundings or environmental modifications [25–27]. However, studies have shown that sensory reweighting is affected by age and is usually impaired in the fall-prone older adults [28,29], affecting the rapid adaptation mechanisms needed to face changing environments [30]. In this context, the manipulation of the sensory and environmental conditions in which a motor task is performed has been used to enhance balance training effects and to increase the variability of the balance training protocols.

Clinically, there have been very few offerings of balance training systems capable of inducing balance perturbations with high levels of unpredictability and modifiable sensory and or environmental conditions to primarily target reactive balance control during overground walking. In this study, we utilized an overground moveable computer-controlled platform with and without overlying obstacles with the aim of implementing a novel perturbation-based balance protocol in various environmental contexts (Figure 1). The first aim of this study was to examine the feasibility, assessing acceptability, practicality, and safety, of the presented perturbation-based balance protocol to induce balance loss from perturbations under various environmental conditions in healthy older adults. We hypothesized that this overground perturbation-based balance protocol would be well accepted by the participants and capable of inducing loss of balance in a safe environment.

A second aim of this study was to test the validity of this novel perturbation-based balance protocol, comparing stability values and behavioral strategies used by the participants in each experimental condition included in the protocol. We hypothesized that the stability values would be lower during loss of balance trials, and that percentage of loss of balance would be higher in the conditions in which the environmental information was more disturbed.

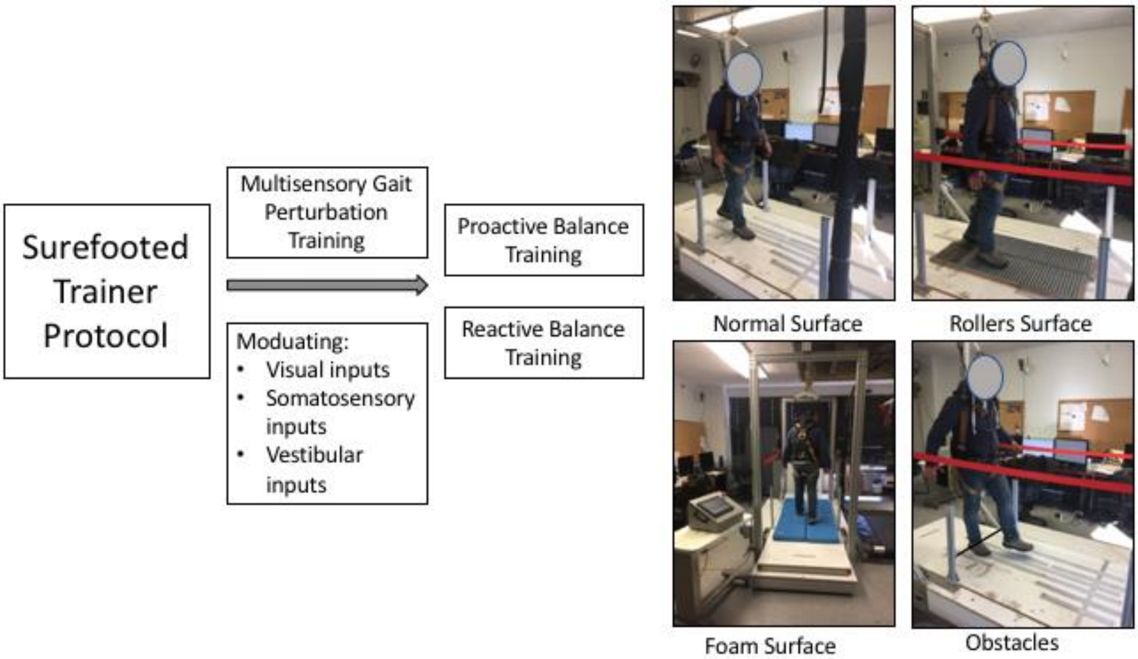

Figure 1. Experimental setup and conceptual framework of the computer-controlled movable platform device (Surefooted Trainer). Forward (Slip-perturbation) and backward (Trip-perturbation) platform displacement was provided for each protocol condition.

2. Materials and Methods

2.1. Participants

In total, 21 healthy older adults (>65 years) (12 females and 9 males) participated in this study. Participants were included if they passed a cognitive test (>26/30 on Montreal Cognitive Assessment Scale) and mobility tests, such as the six-minutes walking test (able to finish the test) [31] and Timed Up and Go (TUG) (score < 13.5 s) [32], to ensure that they were all independent ambulators without cognitive, balance, and gait impairments. Participants were excluded if any of the following medical issues occurs at baseline measurements: Heart rate > 85% of age-predicted maximal heart rate (HR max), systolic blood pressure (SBP) > 165 mmHg and/or diastolic blood pressure (DBP) > 110 mmHg during resting, oxygen saturation (measured by pulse oximeter) during resting <93%, and short of breath during the walking tests included in the baseline assessment protocol. Individuals were also excluded if they reported any neurological, musculoskeletal, or other systemic disorders that would affect the subject's postural control and/or gait functions. Finally, participants were asked about their medical history and if they were under a particular or permanent medical treatment. In this context, participants on sedative drugs; psychotropic medications, such as benzodiazepines; antidepressants; or pain killer medications, such as morphine and oxycodone, were also excluded. These exclusion criteria were established for safety (ability to safely follow instructions and complete the study). Additionally, the NASA task load index (NASA TLX), a clinical tool for measuring subjective mental workload and the Fatigue severity scale (FSS), a 9-item scale which measures the severity of fatigue and its effect on person's activities, were used during the proposed protocol. Demographic details and baseline clinical assessments are presented in Table 1. None of the participants were classified as a faller or reported a history of falling repeatedly. In total, 11 of the 21 patients reported having fallen in the last year at least once. However, for the present study, having or not having experienced a fall was not included in the exclusion criteria. Similarly, leg dominance was not considered as a factor to exclude or include participants into the study. All participants provided written informed consent and this study was approved by the corresponding Institutional Review Board.

Table 1. Participants' demographic data.

Demographics Data	Values
Age (years)	66.7 ± 4.4
Weight (Kg)	79.1 ± 10.05
Height (cm)	173.67 ± 6
MOCA test	27.7 ± 1.8
6 MWT (m)	431.60 ± 57
TUG (s)	7.3 ± 2.2
FSS	4.1 ± 2.4
BBS	54.2 ± 1

Table 1 shows mean and standard deviations (SD) of perturbation trials experienced for all the participants during the protocol and results of NASA-TLX.

2.2. Computer-Controlled Movable Platform Device

In this study, we utilized an overground moveable computer-controlled platform called the Surefooted Trainer, capable of inducing backward and forward perturbations on regular, slippery, and foam surfaces, with and without overlying obstacles. This moveable platform was used to implement a novel perturbation-based balance protocol in various environmental contexts (Figure 1). Participants were asked to walk over a 4 by 2 m custom-made overground computer-controlled movable platform (the Surefooted Trainer) at their regular speed (Figure 1). Platform displacements were induced by the device software that moves the platform 33 cm forward and backward at 0.36 m/s seconds with an acceleration of 7.2 m/s^2. The movable platform is placed over a 5 by 3 m static base (not movable platform). Note the platform allows two displacement settings 16 and 33 cm. To assess responses at the highest intensity, we used 33 cm displacement for the study. For more details regarding the interventional device visit surefootedtech.com.

2.3. Experimental Protocol

Participants were asked to walk over the Surefooted Trainer under 7 different conditions wearing a safety harness. Each condition lasted for 4 min and consisted of 4–6 perturbation trials delivered (variation of the number of perturbation trials was due to the differences in walking speed between participants). The perturbations were induced by moving the platform in a forward direction or backward direction and were programmed to occur near the middle of the platform, but not at a fixed location. Specifically, the perturbation onset was 2.30 s after participants started walking. The software of the Surefooted Trainer recognizes as time zero (gait start) the moment of separation between two load cells located at the beginning of the safety rail and at the top of the participant's harness. Thus, the load cell was used to detect when the carriage for the safety harness moved from its starting position as well as to set the start time for each 4-min condition. All the participants were naive to the type of perturbations included in our experimental protocol, and no practice or familiarization trials were included. The order in which the training conditions were delivered was not randomized. The characteristics of each training condition are explained in Table 2.

Table 2. Characteristics of experimental conditions.

Protocol Condition	Hazards	Type of Perturbation
Condition1 (SlipNorm)	Regular surface	Slip-like perturbation
Condition 2 (SlipRol)	Slippery surface (walking over two 1.2 × 0.30 metallic rollers).	Slip-like perturbation
Condition 3 (TripOB)	Regular surface with two elastomeric cables placed at a height of 100 mm as obstacles.	Trip-like perturbation
Condition 4 (SlipFoam)	Foam surface	Slip-like perturbations
Condition 5 (TripOBFoam)	Foam surface with two elastomeric cables placed at a height of 100 mm as obstacles.	Trip-like perturbations
Condition 6 (SlipTripFoam)	Foam surface	Slip and trip-like perturbations
Condition 7 (SlipTripOBFoam)	Foam surface with two elastomeric cables placed at a height of 100 mm as obstacles.	Slip and trip-like perturbations

Abbreviations: SlipNorm, slip-perturbation on normal surface condition; SlipRol, slip-perturbation on rollers surface condition; SlipFoam, slip on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface.

During the first minute of each condition, participants did not experience any perturbations (natural walking trials). During the next 3 min single (slip or trip) or mixed (both slip and trip) perturbations were experienced. Slip-like perturbations are defined as forward perturbations and trip-like perturbations are defined as backward perturbations (in relation to the direction of walking). Participants were instructed, "when you experience a forward or backward platform displacement, try to keep walking on the platform." A one-minute break between each condition was provided. Subjective workload due to the perturbation -based protocol was assessed by NASA TLX, a subjective multidimensional assessment tool that rates perceived workload to assess a task [33].

2.4. Data Collection

Full body kinematics were collected using an eight-camera 3D motion capture system recording at 120 Hz (Motion Analysis, Santa Rosa, CA, USA). A Helen Hayes marker set with 30 markers was used, such that 29 markers were placed on specific bony landmarks to compute each subject's center of mass (COM) position and one marker was placed on the platform to determine perturbation onset. Data from reflective markers was low pass filtered through a fourth order Butterworth filter with a cut-off frequency of 6 Hz. The weight exerted on the harness for each trial was measured by the load cell that was synchronized with the motion capture system and connected in series with the harness. Custom written algorithms in MATLAB version 2014b (The MathWorks Inc., Nactick, MA, USA) were used to compute all kinematic variables.

2.5. Outcome Measures

2.5.1. Feasibility

To determine the feasibility of our protocol, we evaluated the acceptability, practicality, and safety of our proposed intervention [34]. Acceptability was defined as how the individuals reacted to the protocol [34]. We evaluated this by examining: (1) adherence to the protocol, which was defined as if participants completed the study session or not; (2) number perturbations trials performed for each participant (to show that each participant received similar exposure to all conditions); and (3) how mentally and physically demanding was the protocol for the participants through NASA TLX [33]. Practicality is the extent to which an intervention can be delivered when resources, time, and/or participant commitment are constrained in some way [34]. In our study practicality was documented by the equipment, space, time (participant and personnel), and number of personnel needed. Safety was determined by tracking adverse events. The definition of an adverse event was any incident that caused a participant to temporarily stop or halt the protocol execution [35]. We anticipated non-serious adverse events of muscle soreness and nervousness based on our previous experience administering treadmill-delivered and over ground perturbation-based training protocols.

2.5.2. Behavioral Results

The observed motor behaviors in response to the perturbation trials given by the computer-controlled moveable platform across the seven training conditions was classified in groups depending on whether or not the perturbation induced a fall and/or loss of balance.

Strategies classification:

- Baseline or natural walking trials: trials in which no perturbation was induced;
- Loss of balance;
- No loss of balance.

2.5.3. Validity

During the experiment, one research member classified the behavioral strategies after each perturbation trial as loss of balance or no loss of balance. A backward loss of balance was classified as a posterior displacement of the COM with respect to the base of support accompanied by a backward step [36]. On the other hand, a forward loss of balance was defined as a quick anterior displacement of the COM with respect of the base of support accompanied by one or multiple forward steps [37,38]. Then, after data collection, all the behavioral strategies were confirmed or modified, observing the videos of each perturbation trial collected during the experiment. Finally, all the loss of balance and no loss of balance trials were compared with a commonly accepted measure of stability (the margin of stability (MOS)) [39,40] to corroborate that the behavioral strategies observed after each perturbation trial induced with the Surefooted Trainer were correlated with objective biomechanics outcome measures. Additionally, to test the variability on walking speed between participants, we calculated the average velocity of the sacrum marker in the antero-posterior direction prior the perturbation onset (100 ms before the perturbation onset) and during the natural walking trials.

Margin of Stability

The margin of stability (MOS) is defined as the distance between a velocity adjusted position of the COM and the edge of an individual´s base of support at any given instant in time. It has been shown that MOS is directly related to the impulse required to cause instability [39,40]. This variable was analyzed in 20 participants, including 383 trials, and the time between the first touch-down (TD) before the perturbation and the TD after the perturbation was considered. The foot TD was identified as the instant of initial contact of the foot (heel or metatarsal marker) with the platform when the Z-trajectory of foot marker reached the baseline (i.e., position during quiet stance).

MOS was calculated using the equation below, and then normalized by BOS length:

$\mathrm{MOS} = \mathrm{COM} + \mathrm{COMv}/\sqrt{(g/l)} - \mathrm{BOS}_{max}$. Here, COM indicates the position of COM, which was estimated by the sacrum marker, COMv indicates the velocity of COM in the anterior–posterior direction, "l" indicates the leg length, and BOS_{max} indicates the edge of the base of support. The BOS length was calculated as foot length in a single stance phase, and distance between toe of the leading foot and heel of the trailing foot in double stance phase. As we have 2 types of perturbations (backward and forward platform displacement), the MOS in our study was used to represent postural stability after both posterior and anterior platform displacement. In this context, MOS was normalized by the length of BOS, therefore $0 < \mathrm{MOS} < 1$ represents a stable status, as the CoM or xCoM will be located inside the BOS. Thus, while larger MOS (>1) represent a better posterior stability (for forward platform displacement) but worse anterior stability (for backward platform displacement), as the COM will exceed the anterior boundary of BOS, smaller MOS (<0) represent a worse posterior stability (for forward platform displacement) but better anterior stability (for backward platform displacement), as the COM will exceed the posterior boundary of BOS. Therefore, both MOS for backward platform displacement and MOS for forward platform displacement were normalized by the length of BOS in our study, using the equations shown below:

Norm_MOS_forward platform displacement = $(XCOM - BOS_{min})/BOS\_length = -0.22/0.3 = -73\%$ (XCOM exceed the heel 73% of BOS length in backward)

Norm_MOS_backward platform displacement = $(BOS_{max} - XCOM)/BOS\_length = -0.12/0.3 = -40\%$ (XCOM exceed the toe 40% of BOS length in forward)

As $BOS\_length = BOS_{max} - BOS_{min}$

Norm_MOS_backward platform displacement = $(BOS_{max} - BOS_{min} + BOS_{min} - XCOM)/BOS\_length$

$= 1 - (XCOM - BOS_{min})/BOS\_length$

$= 1 -$ Norm_MOS for forward platform displacement.

From the above equation, we can tell that Norm_MOS_slip could be used for both slip and trip perturbations. For slips, when this variable is negative (<0), the COM status would be unstable, while for trips, when this variable is >1, Norm_MOS_trip (1 − Norm_MOS_slip) would be negative, and the COM status would be unstable. Therefore, only the normalized MOS was used in our study. Additionally, in this study, MOS at recovery touchdown and mean MOS were compared across four different outcomes.

Trunk Angle

The trunk angle (in degrees) was computed from the position of bilateral hip and shoulder markers at compensatory step TD with respect to vertical orientation in the sagittal plane. More negative values signified greater backward trunk extension, while more positive values signified greater forward trunk flexion at compensatory step TD. The maximum trunk angle was also calculated as the peak value from perturbation onset to recovery TD.

Step Length

Recovery step length was measured as the heel-to-heel distance between the foot of the supporting limb and the recovery foot at compensatory step TD.

2.5.4. Data Synthesis

To analyze an overall effect of each condition of the presented experimental protocol, statistical analysis was performed, including all the perturbation trials (forward and backward balance disturbances). Since the first compensatory step is the most important to re-establish BOS for postural stability and not all the participants did not perform multiple stepping following perturbations, for statistical and stability outcome variables analysis, only the first compensatory step was considered. As COM stability value is one of the principal outcome measures, we used this variable to estimate the optimal sample size. Using data from [21], in which the changes in stability values observed after the intervention showed a large effect size (0.80), the sample size was calculated with an acceptable alpha risk of 0.05, an acceptable beta risk of less than 0.8 and estimated loss of 5% of participants. Thus, it was found that 20 participants were needed to achieve the aims proposed for this study.

2.5.5. Statistical Analysis

To examine the participants' performance for each experimental condition, MOS values, step length of the first compensatory step after perturbation, and trunk angle were averaged across conditions for each participant. Then, to examine the effect of each condition on reactive balance strategies, repeated measure ANOVA was conducted on MOS for all conditions included in the protocol, on step length for all the forward balance perturbation trials included in the protocol, and on maximum trunk angle for all the backward perturbation trials included in the protocol, a post hoc paired *t*-test was conducted to identify the conditions in which participants showed lower performances. To compare the kinematics variables (MOS, step length, and trunk angle) between natural walking trials, loss of balance trials, and no loss of balance trials, a Brown–Forsythe test for unequal variance and sample size and post hoc paired *t*-test was also conducted on these variables across all the mentioned outcomes for forward and backward balance perturbations. Specifically, MOS and step length was compared for forward balance perturbation trials, while MOS and maximum trunk angle were compared for backward balance perturbation trials. To test the effect of walking speed on stability values for both forward and backward perturbations across all the condition included in the protocol, an analysis of covariance (ANCOVA) was conducted using MOS as dependent variable, behavioral outcome after perturbation (loss of balance or no loss of balance) as fixed factor, and walking speed as covariable. To evaluate the adaptative changes to perturbations in each experimental condition, paired *t*-test were performed between first and last perturbation trials for each condition included in the protocol. The sample size of this study was estimated based on the stability calculated during treadmill-induced forward and backward perturbations in our previous studies. According to our data, a sample of 21 participants could provide a power $\geq$ 88% at a two-sided alpha level of 0.05 to detect the differences in stability between natural walking trials and forward platform displacements trials with loss of balance, as well as between forward platform displacement trials with and without loss of balance. Similarly, this sample size could also provide a power $\geq$ 83% to detect differences in stability values for forward platform displacement trials. The statistical significance was set at $p < 0.05$, and all the statistical analyses were performed using SPSS 24.00 (IBM Inc., Chicago, IL, USA).

3. Results

In total, 20 participants (12 females and 8 males) completed the study. Demographic information (age, weight, height) and baseline gait and balance abilities can be found in Table 1. Additionally, the scores of the MOCA test (28.3 $\pm$ 2.6) indicated that participants were cognitively healthy, and Fatigue Severity Scores (FSS) showed that participants' activities and lifestyle were not affected by fatigue.

3.1. Feasibility

Overall, 20 out of the 21 participants completed the protocol including all seven conditions. Only 1 participant dropped out due to fear of falling caused by the characteristics of the device, reporting that the level of difficulty of SlipRol condition was too high, increasing fear of falling. Across the entire study, participants demonstrated the ability to perform a similar number of forward platform displacement (16.25 $\pm$ 4.7) and backward platform displacement trials (12.55 $\pm$ 3.5). In addition, NASA TLX results indicated that the perturbation-based balance protocol proposed in this study did not induce subjective mental workload in the participants (Table 3). Regarding the safety of the protocol, there were no serious or non-serious adverse events.

Table 3. Amount of perturbation trials experienced and NASA Task Load index results.

Variables	Results
Slip-perturbation repetitions	18 $\pm$ 4.7
Trip-perturbation repetitions	14.4 $\pm$ 3.5
NASA-TLX	
Mental demand	3.4 $\pm$ 6.7
Physical Demand	13.4 $\pm$ 24.6
Temporal Demand	5.1 $\pm$ 13.6
Performance	67.4 $\pm$ 33.8

Table 3. *Cont.*

Variables	Results
Effort	55.7 ± 16.4
Frustration Level	4.7 ± 4.8
Global Score	24.95

Table 3 shows mean and standard deviations (SD) of perturbation trials experienced for all the participants during the protocol and results of NASA-TLX. Abbreviations: NASA-TLX, NASA Task load index.

3.2. Behavioral Outcomes

A total of 283 loss of balance trials were observed during the Surefooted Trainer perturbation protocol. Conditions SlipFoam (73.7%), SlipRol (80%), SlipTripFoam (77.5%), and SlipTripOBFoam (75%) were the forward platform displacement conditions in which the highest percentage of loss of balance was induced among all the participants (Table 4).

Table 4. Percentage and number of losses of balance trials for each training condition.

Study Conditions	% of Trials That Resulted in LoB or Fall	N of Trials That Resulted in LoB or Fall	N of Perturbation Trials for Each Condition	N of Trials (Total)
SlipNorm	45.8%	39 (1.95 + 0.2)	85 (4.25 + 0.3)	332 (16.6 + 2.4)
SlipRol	73.7%	59 (2.95 + 0.3)	80 (4 + 0.2)	218 (10.9 + 1.1)
TripOB	20.6%	18 (0.9 + 0.3)	87 (4.35 + 0.4)	249 (12.4 + 1.5)
SlipFoam	80%	64 (3.2 + 0.3)	80 (4 + 0.2)	264 (13.2 + 1.5)
TripOBFoam	26.1%	22 (1.1 + 0.4)	84 (4.2 + 0.2)	276 (13.8 + 1.2)
SlipTripFoam (sliptrials)	77.5%	31 (1.55 + 0.2)	40 (2 + 0.1)	109 (5.4 + 0.6)
SlipTripOBFoam (trip trials)	15%	6 (0.3 + 0.5)	40 (2 + 0.1)	100 (5 + 0.6)
SlipTripFoam (slip trials)	75%	30 (1.5 + 0.3)	40 (2 + 0.1)	111 (5.5 + 0.6)
SlipTripOBFoam (trip trials)	35%	14 (0.7 + 0.5)	40 (2 + 0.1)	100 (5 + 0.6)

Abbreviations: SlipNorm, slip-perturbation on normal surface condition; SlipRol, slip-perturbation on rollers surface condition; SlipFoam, slip on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface.

3.3. Validity

Using the behavioral classification (no loss of balance or loss of balance) conducted by comparing the trial record sheet filled out during the experiment with the video recordings of each trial, biomechanical outcome measures (margin of stability, step length, and maximum trunk angle) were compared between natural walking trials, no loss of balance trials, and loss of balance trials.

3.3.1. Margin of Stability

Analyzing MOS values during forward platform displacement perturbation trials, for conditions SlipNorm, SlipRol, and SlipFoam, there were significant differences in MOS between natural walking, no loss of balance, and loss of balance trials ($F(2,91) = 75.14$, $p < 0.001$), ($F(2,80) = 88.68$, $p < 0.001$), and ($F(2,91) = 102.3$, $p < 0.001$), respectively. Post hoc analysis revealed that MOS values were significantly lower in loss of balance trials compared to natural walking and no loss of balance trials ($p < 0.001$) (Figure 2A–C). For forward platform displacement perturbation trials of conditions SlipTripFoam and SlipTripOBFoam, there was a statistically difference in MOS between natural walking, no loss of balance and loss of balance trials ($F(2,79) = 67.92$, $p < 0.001$) and ($F(2,78) = 73.89$, $p < 0.001$). Post hoc analysis revealed that MOS values were significantly lower in loss of balance trials compared to natural walking and no loss of balance trials ($p < 0.001$) (Figure 2D,E).

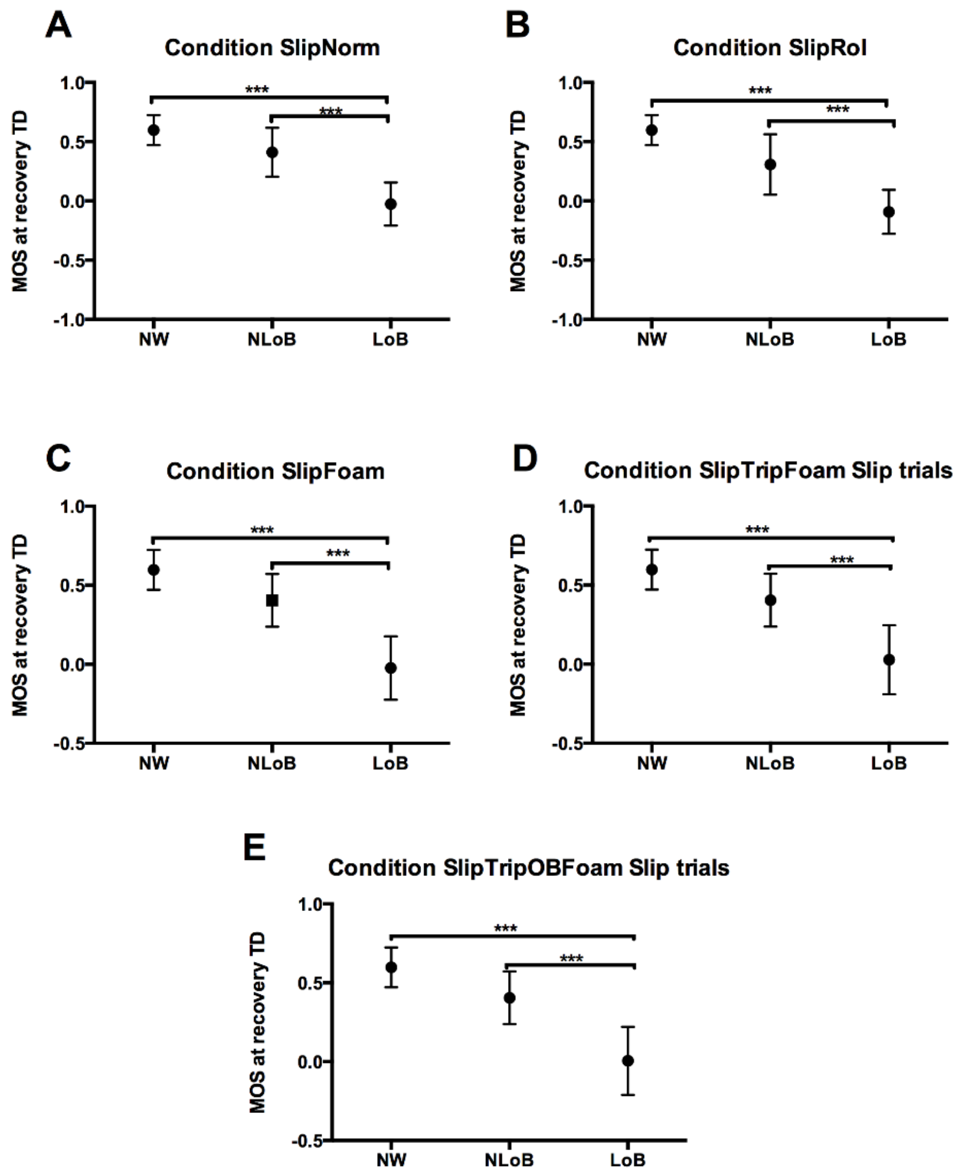

Figure 2. The means and standard deviations (SD) of margin of stability (MOS) at the recovery touch down (TD) for 20 participants during the natural walking (NW) trials (trials in which no perturbation were induced), during the trials in which forward platform displacement did not induce a loss of balance (NLoB), and during the trials in which the forward platform displacement induced a loss of balance (LoB) in conditions SlipNorm, SlipRol, SlipFoam, and for slip-perturbation trials of conditions SlipTripFoam and SlipTripOBFoam. Abbreviations: MOS, margin of stability; TD, touch down; NW, natural walking; NLoB, no loss of balance; LoB, loss of balance; SlipNorm, slip-perturbation on normal surface condition; SlipRol, slip-perturbation on rollers surface condition; SlipFoam, slip-perturbation on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface. *** $p < 0.001$.

Regarding MOS values during backward platform displacement perturbation trials, for conditions TripOB, and TripOBFoam there were no statistically differences between natural walking, no loss of balance, and loss of balance trials ($F(2,83) = 4.38$, $p = 0.062$) and ($F(2,91) = 5.018$, $p < 0.056$) (Figure 3A,B). For backward platform displacement perturbation trials of conditions SlipTripFoam and SlipTripOBFoam, there were no differences in MOS between natural walking, no loss of balance, and loss of balance trials ($F(2,74) = 1.368$, $p = 0.26$) ($F(2,82) = 0.8279$, $p = 0.44$) (Figure 3C,D). Additionally, after conducting an analysis of covariance (ANCOVA), a significant effect of outcome (loss of balance and no loss of balance) was observed on stability values after controlling walking speed, for forward platform displacement trials F(2, 257) = 46.763, $p < 0.01$, and for backward platform displacement trials F(2,156) = 41.157, $p < 0.01$.

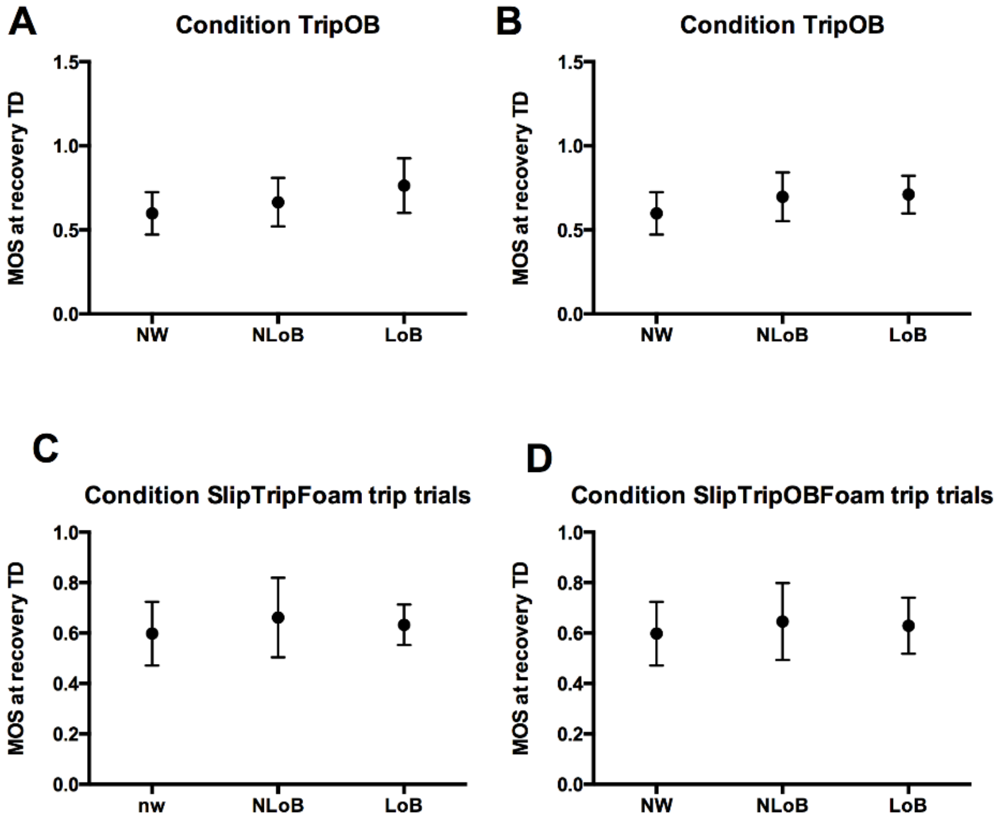

Figure 3. The means and standard deviations (SD) of margin of stability (MOS) at the recovery touch down (TD) for 20 participants during the natural walking (NW) trials (trials in which no perturbation were induced), during the trials in which backward platform displacement did not induce a loss of balance (NLoB), and during the trials in which the backward platform displacement induced a loss of balance (LoB) in conditions TripOB and TripOBFoam, and for trip-perturbation trials of conditions SlipTripFoam and SlipTripOBFoam. Abbreviations: TripOB, Trip-perturbations with obstacles; TripOBFoam, Trip-perturbations with obstacles on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface.

3.3.2. Step Length

For step length at the recovery step after forward platform displacement perturbations trials, in conditions SlipNorm, SlipRol, and SlipFoam there was a significant differences between natural walking, no loss of balance, and loss of balance trials (F(2,91) = 83.72, $p < 0.001$) (F(2,80) = 148.2, $p < 0.001$), and (F(2,91) = 142.5, $p < 0.001$). Post hoc analysis revealed that step length values were significantly lower in loss of balance trials compared to natural walking and no loss of balance trials ($p < 0.001$) (Figure 4A–C). For forward platform displacement perturbation trials of conditions SlipTripFoam and SlipTripOBFoam there were significant differences in step length between natural walking, no loss of balance, and loss of balance trials (F(2,79) = 118.3, $p < 0.001$) (F(2,78) = 93.05, $p < 0.001$). Post hoc analysis revealed that step length values were significantly lower in loss of balance trials compared to natural walking and no loss of balance trials ($p < 0.001$) (Figure 4D,E).

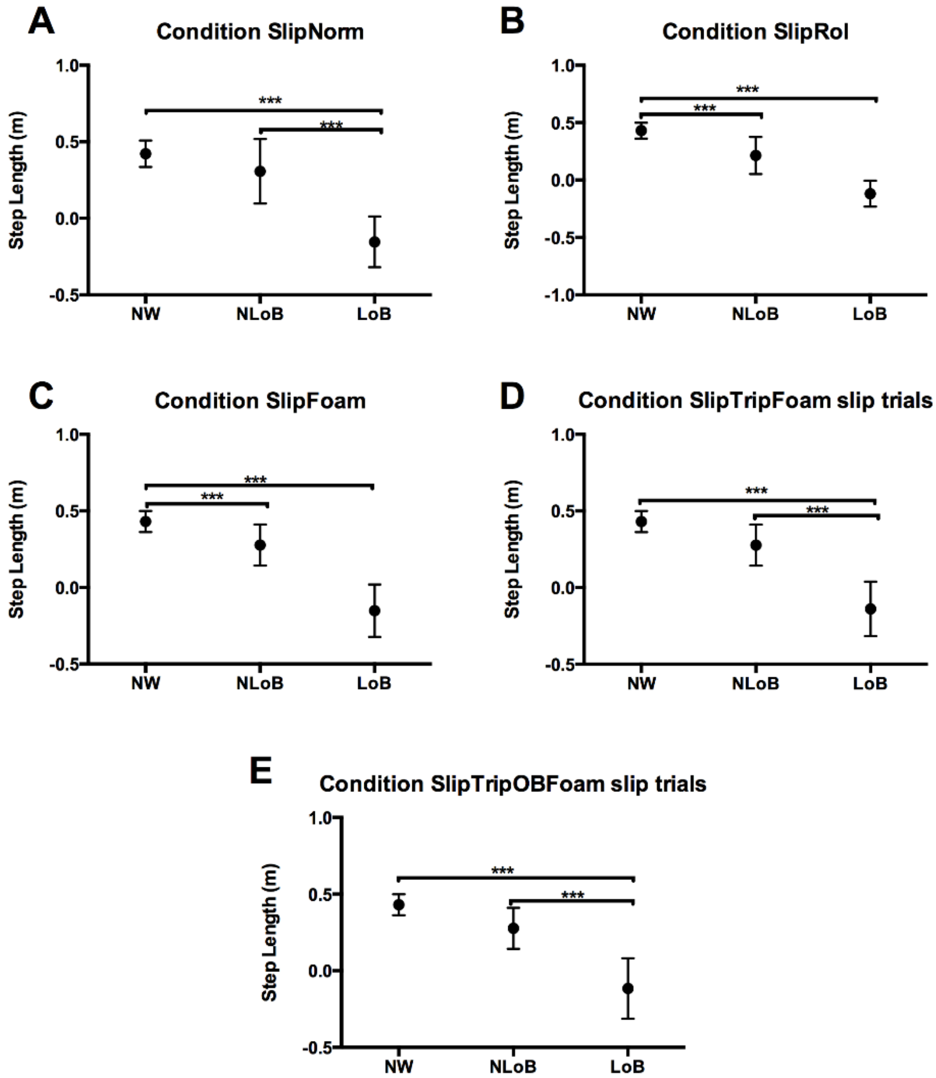

Figure 4. The means and standard deviations (SD) of step length at the recovery touch (TD) down values for 20 participants during the natural walking (NW) trials (trials in which no perturbation were induced), during the trials in which forward platform displacement did not induce a loss of balance (NLoB), and during the trials in which the forward platform displacement induced a loss of balance (LoB) in conditions SlipNorm, SlipRol, SlipFoam, and for slip-perturbation conditions SlipTripFoam and SlipTripOBFoam. Abbreviations: m, meters; SlipNorm, slip-perturbation on normal surface condition; SlipRol, slip-perturbation on rollers surface condition; SlipFoam, slip-perturbation on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface *** $p < 0.001$.

3.3.3. Maximum Trunk Angle

For maximum trunk angle after backward platform displacement perturbations, there were significant differences between natural walking, no loss of balance, and loss of balance trials in TripOB and TripOBFoam conditions ($F(2,83) = 26.47$, $p < 0.001$) ($F(2,91) = 12.87$, $p < 0.001$). Post hoc analysis revealed that maximum trunk angle values were significantly higher in loss of balance trials compared to natural walking and no loss of balance trials ($p < 0.001$) (Figure 5A,B). For backward platform displacement perturbation trials in conditions SlipTripFoam and SlipTripOBFoam there were significant differences between natural walking, no loss of balance, and loss of balance trials ($F(2,74) = 1.368$, $p = 0.026$) ($F(2,82) = 12.87$, $p = 0.044$). Post hoc analysis revealed that for SlipTripFoam maximum trunk angle values were significantly higher in loss of balance trials compared to natural walking ($p < 0.001$), however no differences were observed between no loss of balance and loss of balance trials ($p = 0.12$) (Figure 5C), and for SlipTripOBFoam maximum trunk angle values were significantly higher in loss of balance trials compared to natural walking and no loss of balance trials ($p < 0.001$) (Figure 5D).

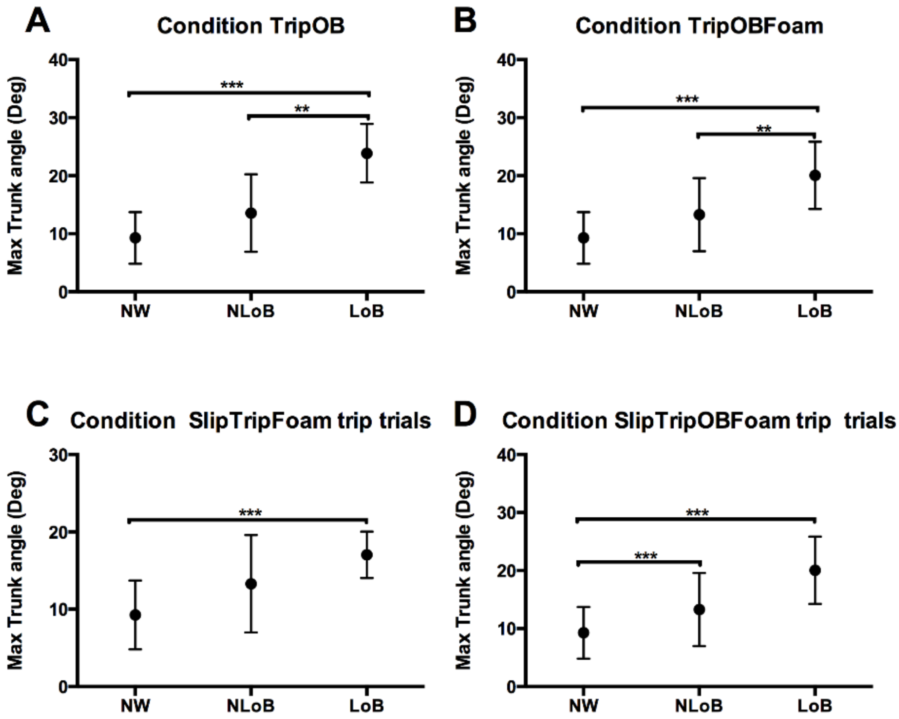

Figure 5. The means and standard deviation (SD) of maximum trunk angle average values for 20 participants during natural walking trials (NW) (trials in which no perturbations were induced), during the trials in which backward platform displacement did not induce a loss of balance (NLOB), and during the trials in which the backward platform displacement induced a loss of balance (LoB) in conditions TripOB and TripOBFoam, and for trip-perturbation trials of conditions SlipTripFoam and SlipTripOBFoam. Abbreviations: Deg, degree; TripOB, Trip-perturbations with obstacles; TripOBFoam, Trip-perturbations with obstacles on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface. *** $p < 0.001$, ** $p < 0.01$.

Considering all the trials (no loss of balance and loss of balance), there was a significant difference in MOS between the training conditions included in the Surefooted protocol as determined by repeated measure ANOVA ($F(7,482) = 41.92$, $p < 0.001$). Post hoc analysis revealed that conditions SlipRol, SlipFoam, and forward platform displacement perturbation trials for conditions SlipTripFoam and SlipTripOBFoam were the most unstable training conditions compared to natural walking trials (the trials with no perturbations) ($p < 0.001$) (Figure 6A), and that MOS was not significantly different in conditions TripOB, TripOBFoam, and backward platform displacement perturbation trials for conditions SlipTripFoam and SlipTripOBFoam compared to natural walking trials (Figure 6B). Similarly, there was a significant difference in the step length at the first recovery step between the training conditions included in the Surefooted protocol as determined by repeated measure ANOVA ($F(7,484) = 29.30$, $p < 0.001$). Post hoc analysis revealed that conditions SlipRol, SlipFoam, and forward platform displacement perturbation trials for conditions SlipTripFoam and SlipTripOBFoam were the conditions in which participants performed the shortest step length during the first recovery step after perturbations ($p < 0.001$) (Figure 6C), and that step length of the first recovery step were not significantly different in conditions TripOB, TripOBFoam, and backward platform displacement perturbation trials for conditions SlipTripFoam and SlipTripOBFoam compared to natural walking trials (Figure 6D).

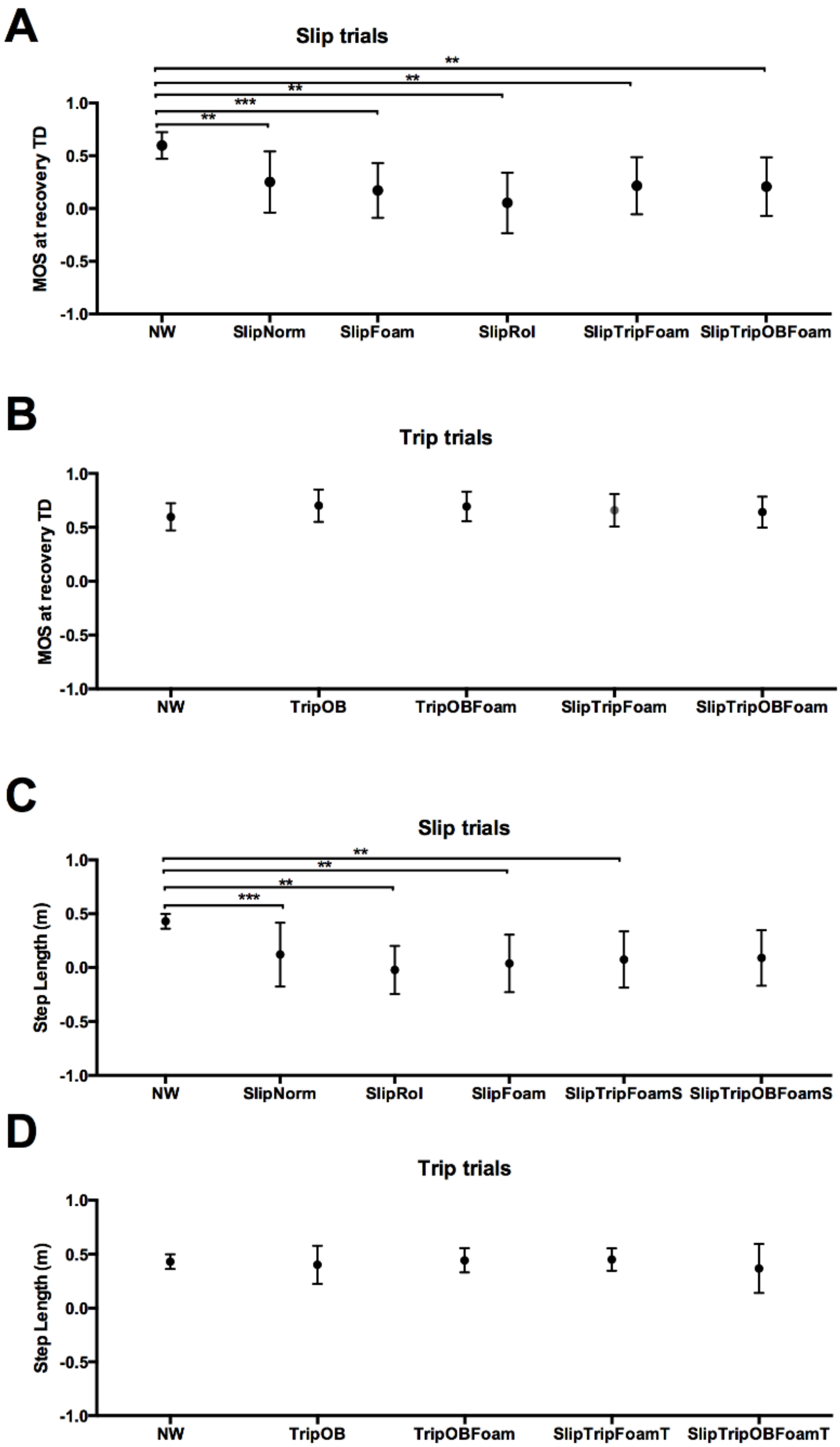

Figure 6. Comparisons of means and standard deviations (SD) of margin of stability (MOS) in forward (**A**) and backward platform displacement (**B**) training conditions compared to natural

walking trials, and comparison of means and standard deviation (SD) of step length at the recovery touch down between training conditions compared to natural walking trials; (**C**): forward platform displacement conditions; (**D**): backward platform displacement conditions. Each condition includes both no loss of balance and loss of balance trials. Abbreviations: MOS, margin of stability;m, meters; NW, natural walking; NLoB, no loss of balance; LoB, loss of balance. SlipNorm, slip-perturbation on normal surface condition; SlipRol, slip-perturbation on rollers surface condition; TripOB, Trip-perturbations with obstacles; SlipFoam, slip-perturbation on foam surface; TripOBFoam, Trip-perturbations with obstacles on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface. *** $p < 0.001$, ** $p < 0.01$.

Regarding the comparison of stability values between the first and the last perturbation trial for each protocol condition included in the study, MOS values were significantly higher in the last perturbation trial compared to the first one in SlipNorm, SlipRol, SlipFoam, and for forward platform displacement perturbation trials of SlipTripFoam and SlipTripOBFoam conditions ($p < 0.01$). No differences were observed for TripOB, TripOBFoam, and backward platform displacement perturbation trials of conditions SlipTripFoam and SlipTripOBFoam (Figure 7).

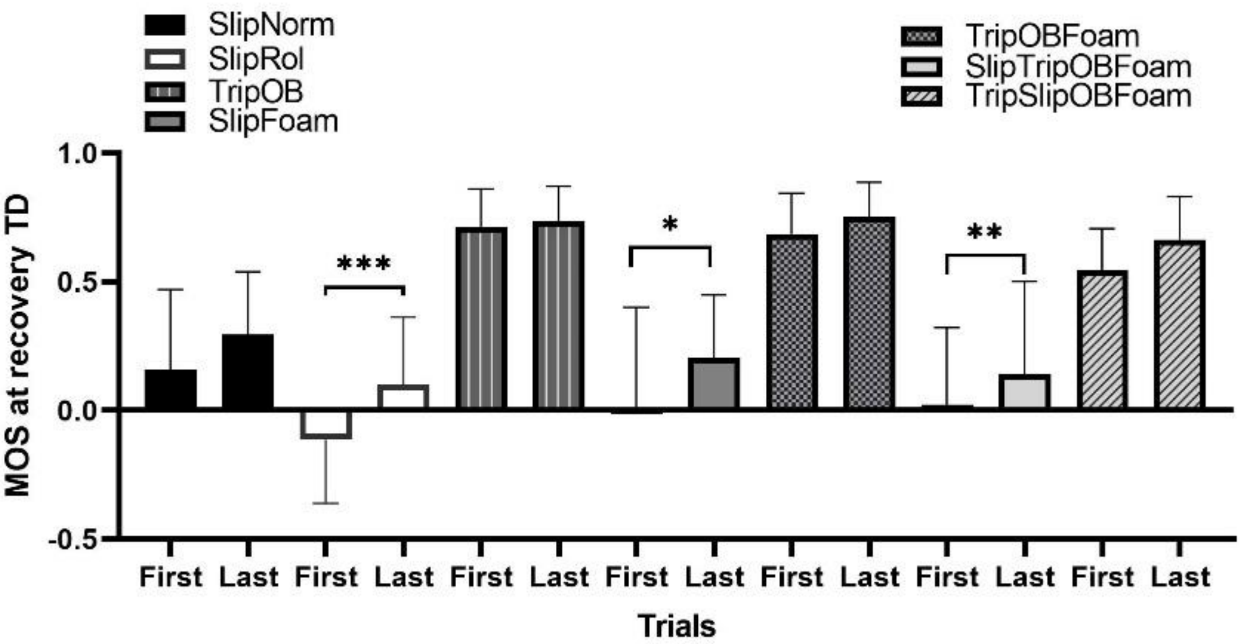

Figure 7. Comparisons of means and standard deviations (SD) of margin of stability (MOS) between the first and the last trial of each condition included in the protocol. Note that for condition SlipTripFoam, the first and the last trials were forward platform displacement trials (backward loss of balance) and that for condition SlipTripOBFoam, the first and last trials were backward platform displacement trials (forward loss of balance). Abbreviations: SlipNorm, slip-perturbation on normal surface condition; SlipRol, slip-perturbation on rollers surface condition; TripOB, Trip-perturbations with obstacles; SlipFoam, slip-perturbation on foam surface; TripOBFoam, Trip-perturbations with obstacles on foam surface; SlipTripFoam, slip and trip-perturbations on foam surface; SlipTripOBFoam, slip and trip-perturbations with obstacles on foam surface. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

4. Discussion

The primary aim of this study was to examine the feasibility of a perturbation-based balance protocol including a novel computer-controlled movable platform to induce balance perturbations under various environmental conditions in healthy older adults. The second aim of this study was to test the validity of this overground computer-controlled movable platform, comparing behavioral and objective biomechanics parameters in seven different sensory walking conditions, to implement a walking perturbation-based protocol in healthy older adults. Our findings indicate that the overground computer-controlled movable platform used in this perturbation-based protocol was capable of safely inducing losses of balance in each condition included in this study in healthy older adults. Additionally, we demonstrated that the perturbation protocol proposed in the present study was acceptable for most participants (20 of 21 participants), and capable of inducing loss of balance. Similarly, we demonstrated that stability values were lower and the percentages of loss of balance were higher during the perturbation trials in which the environmental conditions were more challenging (walking over rollers (SlipRol) and walking over a foam surface (SlipFoam)).

4.1. Feasibility

We determined that the perturbation-based protocol implemented in this study using the Surefooted Trainer was acceptable and safe for nearly all the participants. Only one participant dropped out due to fear of falling caused by the characteristics of the device, reporting that the unpredictability of the perturbation, and the metallic rollers of condition SlipRol increased anxiety and fear of falling. One thing that likely helped maintain adherence in our study was that the difficulty of the protocol increased progressively (starting the intervention asking the participants to walk in a condition without any environmental modifications (SlipNorm condition)). Additionally, given the task-specific approach implicit in perturbation-based interventions, we suspect that giving subjects experience practicing walking with perturbations in a safe environment is beneficial in building confidence, improving falls self-efficacy, and reducing the fear of falling, which, in turn, could have contributed to the high acceptance of the protocol among the participants.

4.2. Validity

For forward platform displacement perturbation protocols (SlipNorm, SlipRol, SlipFoam, SlipTripFoam and SlipTripOBFoam), in the trials in which a loss of balance was induced it was possible to observe significantly lower stability values (MOS and step length) (Figures 2 and 4), which confirmed the capability of the system to induce losses of balance. On the other hand, for backward platform displacement perturbation trials (TripOB, TripOBFoam, SlipTripFoam, and SlipTripOBFoam), the MOS values were similar between loss of balance and no loss of balance trials (Figure 3), however when we assessed trunk angle during the loss of balance trials we observed that in those trials, the maximum trunk angle was higher compared to the no loss of balance trials which can be assumed as an indicator of instability (Figure 5). Along these lines, it has been well described that after experiencing a backward perturbation (posterior displacement of the base of support), the forward compensatory stepping strategy contributes to a counter-clockwise rotational torque that helps to arrest and reduce the trunk flexion angle observed after a forward loss of balance [20]. Thus, it is possible to assume that the more trunk flexion is observed after a backward perturbation, the more postural instability. This allows us to infer that the system was able to induce losses of balance during backward platform displacement perturbation trials, however in a lower magnitude compared to the slip-perturbation conditions.

Stability values (MOS and step length) were significantly lower during forward platform displacement perturbation trials than baseline. However, this was not the case for backward platform displacement perturbations, where MOS for baseline and backward perturbations trials were comparable, showing that those conditions were not as effective or might be less challenging for inducing loss of balance than the forward platform displacement perturbation protocols. Similarly, previous studies have shown a significantly greater proportion of falls during backward loss of balance (forward perturbations) compared to forward loss of balance (backward perturbations) at the same perturbation intensity in different populations [21,41]. Several mechanisms may independently or in combination underlie these directional differences. Grabiner et al. have proposed that arresting backward motion of the trunk during a slip is more challenging than forward trunk movement during a trip, resulting in higher falls incidence during slips, concluding that differences in base of support and signals arising from visual, proprioceptive, and vestibular sensory systems with perturbation direction may be responsible for these results [42].

Similarly, the impact of a forward-directed perturbation may be stronger because the base of support is smaller for backward compensatory strategies (backward recovery step) compared with compensatory strategies performed in forward directions (such as forward recovery step). Additionally, it has been shown that during forward-directed perturbations, the visual information available regarding the compensatory strategies necessary to maintain balance are lower compared to the visual information available during forward loss of balance [29], making visual feedback less effective when perturbed backward, possibly creating difficulty in organizing postural reactions to backward falls [29]. All this could explain, in part, the kinematic outcomes observed in our study, and the lower amount of loss of balance observed in the sessions that included backward platform displacement perturbation trials in our protocol. However, it might be possible that increasing intensity of the backward/forward platform movement (velocity and/or acceleration), and/or increasing the obstacle height, could generate major levels of instability and increase the difficulty of the protocol proposed in this study, especially for trip-perturbation protocols. Additionally, it must be noted that stability values and, hence, perturbation outcomes for both forward and backward perturbations could be affected by walking speed [43]. However, our results indicated that the Surefooted device was able to induce loss of balance and generate postural instability after controlling for this between subjects and within-trial walking speed variability.

4.3. Perturbation-Based Intervention and Sensory Integration

A higher percentage of loss of balance trials (Table 4), and lower stability values (Figure 6) were observed during the protocol conditions in which the walking surface was modified (SlipRol, SlipFoam, SlipTripOBFoam). Along these lines, it has been well described that more sensory noise (such as environmental changes, cognitive interference, delay in the integration of sensory information, etc.) results in less reliable sensory information, which can be compensated by an increased use of the information of the other sensory systems (i.e., sensory reweighting) [44]. Similarly, evidence has shown that the use of proprioceptive information increases, and the vestibular and visual systems deteriorate more with age compared with the proprioceptive system, resulting in more sensory noise in the vestibular and visual information [44]. In our study, the use of rollers, simulating a slippery surface, and foam altered the proprioceptive information during walking, adding more difficulty to react to the perturbation triggered by the computer-controlled moveable platform, which could explain why these conditions resulted in the highest rates of LOB (Table 4).

It has been also well described that a deterioration of the neuromuscular system to sense the boundary of the base of support in relation to the position of the COM, as well as to regain balance after sudden perturbations can be an important risk factor for falls in older adults [7,44,45], and that the control of the COM displacement within the base of support is related more to sensory perception rather than reduced muscle strength [45,46]. In concordance with this evidence, our results showed that MOS values were lower during the conditions in which the somatosensory information was disturbed (SlipRol, SlipFoam, SlipTripFoam and SipTripOBFoam conditions) (Figure 6A,B). Additionally, step length showed negative values during SlipRol, SlipFoam, and in slip-perturbation trials of Slip-

TripFoam and SlipTripOBFoam conditions, which was related to the higher percentage of backward loss of balance experienced by the participants in these conditions (Figure 6C).

Although demonstrating adaptation to the perturbation trial was not one of the primary aims of this study, we observed that the performance was better in the last trials for all the conditions in which a forward balance perturbation was induced compared to the novel trials (first trial of each protocol condition) (Figure 7). This finding is in line with several studies that have shown that healthy older adults can learn and improve their reactive balance strategies even after experience only few balance perturbations trials [13,15,47].

4.4. Limitations of the Study

The following limitations should be considered when interpreting the results of the current study. A common limitation of most of the moveable-platform perturbation systems that try to simulate trip perturbations is that it is not possible to replicate the sensory and motor conditions that arise when the swing phase of gait is obstructed by an external obstacle. However, the Surefooted Trainer's backward platform displacement does create an overall pattern of whole-body motion that is like what occurs following an actual trip (COM displaced forward relative to the anterior most foot). In addition to this backward surface displacement, the inclusion of obstacles (via the tethered rope) makes the forward loss of balance experience more reliable. Another limitation of this study was that we reported data from adherence to the protocol, however it should be considered that the proposed experimental design included a single-session protocol. There may be a potential bias from interpreting data from a single session to draw conclusions about adherence. Similarly, our protocol only included healthy individuals. Future work should extend these initial findings to a larger group, including individuals who suffer from recurrent falls and/or neurological diseases. In addition, environmental conditions included in the present protocol were not considered in a random order. Therefore, results of each condition may be influenced by learning of the previous condition. Finally, the externally induced gait perturbation used in this protocol varied trail to trial and did not occur consistently in a specific moment of the gait cycle (such as swing face, double stance, etc.). This could cause the reactive response to differ from one trial to the other, which could potentially affect the adaptation rate to the balance disturbance.

5. Conclusions

In summary, we have shown that a fall-recovery protocol using an overground computer-controlled moveable platform device is an acceptable, practical, and valid therapeutic tool to develop perturbation-based training for healthy older adults. Our initial results suggest that this new intervention device can safely induce balance loss, which was correlated with improved objective biomechanical stability values for both forward and backward platform displacement perturbations. Additionally, the highest percentage of loss of balance and the lowest stability values were observed in the conditions in which forward platform displacement perturbation trials were induced in combination with proprioceptive disturbances (SlipRol and SlipFoam conditions). Future studies should be conducted to extend this work, examining if fall-resisting skills can be acquired with repeated exposure (perturbation-based training) under all these conditions representing higher levels of unpredictability, diverse environmental conditions and opposing perturbation types (mimicking slips and trips). Future research should also test the preliminary findings observed in this study in a randomized controlled trial and with a larger cohort with more impaired function or in persons with neurological disorders. Finally, future studies should evaluate the intervention's effects on balance self-confidence, amount of time spent walking (walking activity), and whether it can reduce subsequent falls for participants in their normal environments.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of University of Illinois at Chicago (protocol code 2016-0887).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this article are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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