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Research article

Assessing the role of ankle and hip joint proprioceptive information in balance recovery using vibratory stimulation

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ABSTRACT

Background: Previous work suggests that proprioceptive information from ankle and hip are crucial in maintaining balance during upright standing; however, the contribution of these proprioceptive information during stepping balance recovery in not clear. The goal of the current study was to assess the role of ankle and hip proprioceptive information on balance recovery performance by manipulating type 1a afferent in muscle spindles using vibratory stimulation.
Methods: Twenty healthy young participants were recruited (age = 22.2 ± 2.7 years) and were randomly assigned to balance recovery sessions with either ankle or hip stimulation. Trip-like perturbations were imposed using a modified treadmill setup with a protecting harness. Vibratory stimulation was imposed bilaterally on ankle and hip muscles to expose participants to three condition of no-vibration, 40Hz vibration, and 80Hz vibration. Kinematics of the trunk and lower-extremities were measured using wearable sensors to characterize balance recovery performance. Outcomes were response time, recovery step length, trunk angle during toe-off and heel-strike of recovery stepping, and required time for full recovery.
Findings: Ankle vibratory stimulation elicited main effects on reaction time and recovery step length ($p < 0.002$); reaction time and recovery step length increased by 23.0% and 21.2%, respectively, on average across the conditions. Hip vibratory stimulation elicited significant increase in the full recovery time ($p = 0.019$), with 55.3% increase on average across the conditions.
Interpretation: Current findings provided evidence that vibratory stimulation can affect the balance recovery performance, causing a delayed recovery initiation and an impaired balance refinement after the recovery stepping when applied to ankle and hip muscles, respectively.

1. Introduction

Human balance is a complex system that includes sensory units, muscles, and the central nervous system [1,2], and any change in these components, or their interactions, can compromise balance. While several methods have been established to measure the influence of lower-extremity muscle strength deficit in human balance [3], a little is known about the contribution of proprioception

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feedback in balance performance. Proprioceptive inputs normally include cutaneous, visual, and vestibular signals to provide a coherent body scheme, maintain equilibrium, and inform movement [4]. In particular, the representation of the static and dynamic position of the human body might be largely based on muscle proprioceptive inputs that continuously inform the central nervous system about the position of each segment in relation to the others [5]. Proprioceptive information from the lower extremities and trunk muscles play a major role in balance control [6].

Previous work suggests that proprioceptive information from ankle and hip are crucial in maintaining balance during upright standing. Depending on the severity of perturbation, information from one or combination of these proprioceptive areas are implemented in ankle and hip strategy mechanism to maintain the upright balance [7]. Beyond upright standing, experiments have been conducted to understand the contribution of ankle and hip muscles in balance recovery. Treadmill setup has been used previously to expose participants to balance perturbation like tripping. The perturbation involves a sudden backward movement of the belt to move the feet posteriorly and induce a forward loss of balance [8,9]. In response to this perturbation, the sensorimotor system from ankle and hip joints executes a reactive stepping to expand the base of support [8,10]. Based on muscle activity assessment, previous research suggests that proprioceptive signals from the proximal musculature associated with the hip joint are responsible for initiation of the recovery response, while distal proprioception associated with the ankle joint is responsible for completing the recovery step [11]. Nevertheless, all these conclusions are based on the hypothesis that muscle activity onset is directly associated with proprioceptive performance. In this regard, a methodology for directly manipulating proprioceptive performance would provide more insights regarding the contribution of each proprioceptive area (ankle vs. hip) on balance control.

One approach to manipulate proprioception performance is applying vibratory stimulation to muscles, which can influence the performance of type 1a afferent in muscle spindles [12–14]. Signals from muscle spindles are directed to motor neurons, which activate the parent muscles to restore joint position, and vibratory stimulation can affect this short-latency reflexive mechanism [15]. Further, muscle spindles provide essential proprioceptive feedback to the central nervous system for long-latency responses, and vibratory stimulation can alter the conscious perception of movement and limb position [16,17]. Indeed, previous work showed that vibratory stimulation of lower extremities affects upright balance sway among healthy young individuals. These alterations include larger and faster body sway during upright standing when vibratory stimulation is applied to ankle muscles (i.e., plantar flexor muscles) [18–22]. However, the effect of vibratory stimulation on balance recovery has not been studied for different proprioceptive areas. This includes situations where a whole-body response to a large-scale postural perturbation requires one or multiple steps to avert a fall.

The goal of the current study was to identify the effects of altering proprioceptive information from the ankle and hip muscles on balance recovery. First, using baseline balance recovery data without any vibratory stimulation, we determined reliable outcomes to represent balance recovery performance from a treadmill perturbation. Then, by altering the joint muscle proprioceptive performance using vibratory stimulation applied to muscles corresponding to each joint, we investigated the individual contribution of ankle and hip proprioceptive information in balance recovery among a healthy young sample. We implemented a modified treadmill setup to impose a trip-like perturbation and study the kinematics behaviors (i.e., balance recovery) in response to this perturbation. We hypothesized that vibratory stimulation would affect balance recovery, with different effects when applied at the ankle musculature compared to the hip musculature. Based on previous research [11], we expected that vibratory stimulation on proximal hip would significantly alter balance recovery parameters related to recovery initiation (reaction time) and vibratory stimulation on distal ankle area will significantly alter balance recovery behaviors associated with shaping the reactive stepping (execution of the recovery step and achieving steady state walking).

2. Materials and method

2.1. Participants and experimental design

Healthy young adults aged 18–30 years were recruited. All participants were cognitively healthy and without any severe comorbidity that can affect mobility, based on Montreal Cognitive Assessment (MoCA) test for dementia [23] and CMS Hierarchical Condition Category (CMS-HCC) [24]. Participants were excluded if they had history of dizziness, vertigo, and sedating medication, or consumed alcohol within the prior 24 h of testing. All participants were recruited after completing written informed consent according to the principles expressed in the Declaration of Helsinki [25] approved by the University of Arizona's Review Boards. This was a pre-post clinical study including one session of assessment without a control group assignment. There were two types of balance recovery sessions involving vibratory stimulation either on ankle or hip muscles. To minimize the potential learning effects due to balance recovery repetitions, each participant was randomly, based on a Latin square block design, assigned to only one of the balance recovery sessions (ankle or hip stimulation).

2.2. Balance perturbation setup

A specialized treadmill with no hand support (PhysioGait & PhysioMill, HealthCare International, Langley, WA) was used to impose trip-like perturbations [8,26]. To avoid an actual fall, the PhysioGait provides a protection harness to prevent an actual fall. The setup contained an actuator column to make the harness adjustable based on the height of each participant. The yoke assembly on top of the harness included two separate force sensors, which were used to assess the weight tolerated by the harness (Fig. 1A). The length of the lanyard that connected the safety harness to the support structure was adjusted for each participant to avoid actual fall (knees hitting the ground) and at the same time provide enough flexibility so the participant could move one step backward/forward. Participants were asked to stand motionless on the treadmill. The perturbation involves an unexpected sudden backward movement of the belt to move the feet posteriorly and induce a forward loss of balance [8,9]. In response to the perturbation, the sensorimotor system attempts to execute stepping response to expand the base of support and establish a stable gait [8,10] (Fig. 1B & C).

In each session, after practicing twice, each participant went through three sets of treadmill perturbations, with each set including 5 trials (Table 1). Of note, to minimize potential residual effect of vibration and learning effects, practice trials were executed without any exposure to vibratory stimulations and with a low speed of perturbation (max speed of 0.2 m/s of backward belt movement). The three sets corresponded to either low or high frequency vibration or no vibratory stimulation. There was ~5-min rest between trials to minimize potential residual effects of fatigue and vibration [21,27]. Each set includes four tests of sudden backward belt movement with two difficulty levels (two with max speed of 0.35 m/s and two with max speed of 0.7 m/s) and one forward belt movement (max speed of 0.2 m/s). The forward belt movement trial was to help minimize anticipation of perturbation direction. In each trial the treadmill reached the max speed in ~40 msec. Treadmill max speeds and acceleration were selected based on previous studies and our

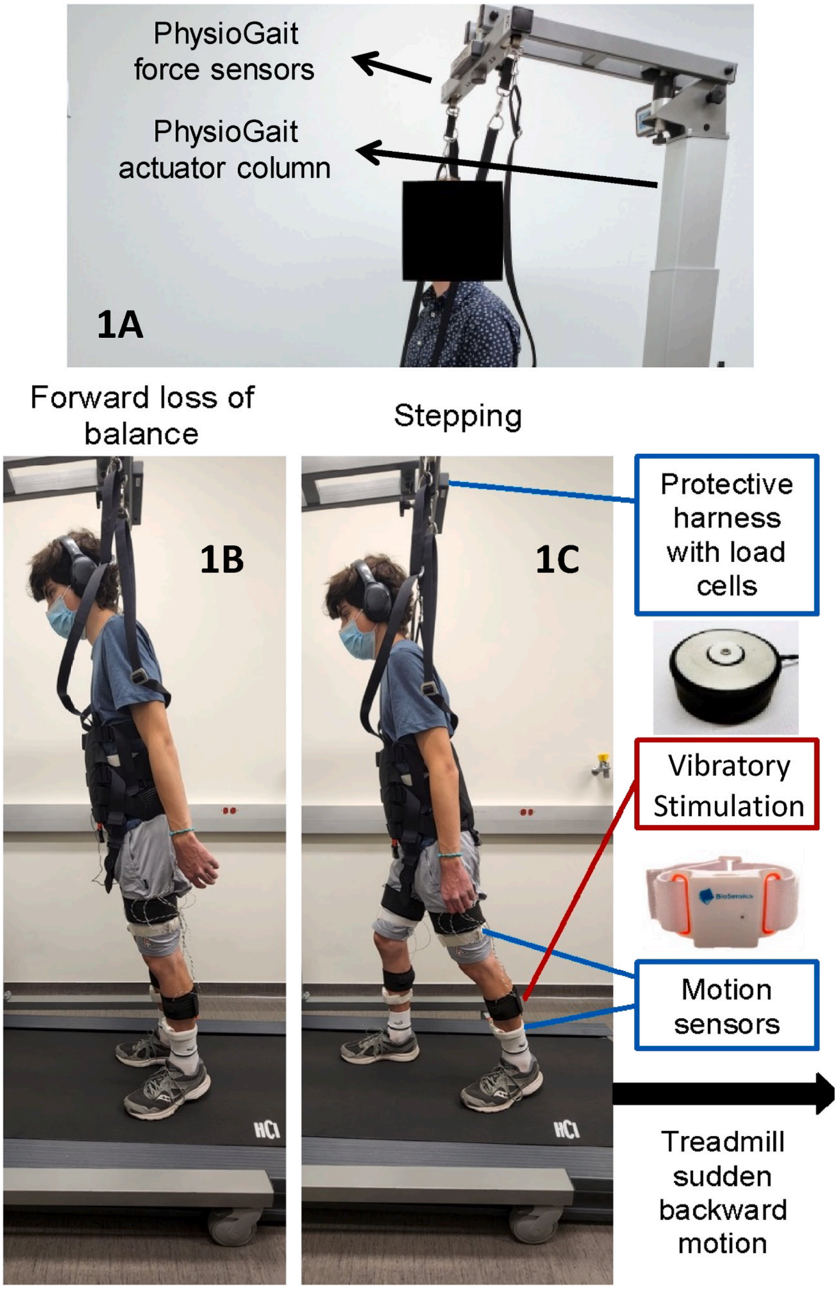

Fig. 1. Treadmill trip-like perturbation. 1A: Adjustable actuator column and force sensors for measuring the weight tolerated by the harness; 1B: Sudden backward movement of the belt to move the feet posteriorly and induce a forward loss of balance; and 1C: Recovery step execution to maintain the balance.

Table 1
Treadmill perturbation exposure. Participants were randomly assigned to ankle or hip vibration trials (each participant was only exposed to vibration at one location of either ankle or hip muscle groups). The order of sets (no vibration and low and high frequency vibration) and trials (0.35, 0.7, or 0.2 m/s speed) were randomized.

Set 1: No Vibration				
Backward 0.35 m/s	Backward 0.7 m/s	Forward 0.2 m/s	Backward 0.35 m/s	Backward 0.7 m/s
Set 2: Ankle (or Hip) Low Frequency Vibration				
Backward 0.7 m/s	Forward 0.2 m/s	Backward 0.35 m/s	Backward 0.7 m/s	Backward 0.35 m/s
Set 3: Ankle (or Hip) High Frequency Vibration				
Forward 0.2 m/s	Backward 0.35 m/s	Backward 0.7 m/s	Backward 0.35 m/s	Backward 0.7 m/s

pilot data [8,28]. Followed by a successful recovery, participants walked until they gained their steady-state walking (at least 20 steps). The order of sets (no-vibration, and low and high frequency), and balance recovery difficulty (treadmill speeds) were randomized to balance potential order effects from fatigue, learning, and vibration residual effects.

Vibratory stimulation was imposed bilaterally on 1) ankle area muscles including tibialis anterior, peroneus longus, soleus, gastrocnemius; or 2) hip area muscles including quadriceps, gluteus medius, and paraspinals [11,29]. Of note, each participant was exposed to either ankle or hip vibration. We chose these muscles for ankle and hip joints because during static and dynamic balance, proprioceptive information from these muscles provides important sources of afferent information for ankle and hip joints and have been the targeted muscles for vibratory stimulation in previous research [19,22,30]. We considered two vibration frequencies for exciting muscle spindles. Previous evidence suggests that in healthy people, 80Hz vibrations of ankle muscles produce the maximal effect on postural balance, and in frequencies below 40Hz the vibration effects may not be consistent and vary between individuals [31–34]. Accordingly, we used Gaussian noise, band-limited to 80Hz for higher frequency and 40Hz for lower frequency stimulations. Magnetic actuator systems (C-2HDLF Tactor, Engineering Acoustics, FL, USA) and a Universal Controller (TDK, Engineering Acoustics, FL, USA) were used to provide the appropriate frequency ranges. The amplitude of the vibration was set to 1 ± 0.002 mm, which is a level found to effectively influence muscle spindle afferents [35,36]. Actuator systems were placed on the belly of targeted muscles with direct contact, for which, each actuator covered a circular surface area of 7 cm^2 (Fig. 1B and C). The placements of actuators were fixed using Velcro. Targeted muscles were exposed to stimulation for 1 min before the start of each testing to assure that effects of stimulation reach a plateau level [21,37], and were on until the end of each trial.

2.3. Balance recovery outcomes

Failing to recover from the perturbation was identified when more than 30% of the body weight was supported by the harness (measured by the maximum force tolerated by the harness force sensors) [8,26,38]. Recoveries with integrated weight support greater than 5% of the body weight × second, during the recovery period (from the start of the perturbation until the first recovery foot heel strike), were classified as harness-assisted recoveries [26]. All other recoveries were considered successful and were used for extracting balance recovery outcomes. Three-dimensional acceleration and angular velocity of shins, thighs, and the trunk were measured using five wearable motions sensors (LEGSys™, BioSensics LLC, Boston, MA, sampling frequency = 100Hz), to derive balance recovery and gait outcomes using our previously established methods [39,40] (Fig. 1B & C). The signals from the sensors were filtered to remove noise and drift (first-order high pass butter-worth filter with a cutoff of 2.5Hz). Demographic information along with shin and thigh lengths were measured during data collections, for the purpose of extracting balance recovery outcomes. Balance recovery outcomes included response time, recovery step length, trunk angle during toe-off and heel-strike of recovery stepping, and required time for full recovery (see Table 2 for definitions).

2.4. Statistical analysis and power calculation

Two types of statistical analyses were performed. First, to investigate the effect of vibratory stimulation on balance recovery, we examined the association between balance recovery outcomes (Table 2) and vibration conditions (no vibration, 40Hz, and 80Hz

Table 2
Balance recovery outcomes – Outcomes related to fall risk are selected based on previous research. Average ICC values are reported across treadmill perturbation conditions.

Outcome	Definition	ICC[a]
Reaction time	Time from the onset of treadmill motion to recovery step toe-off	0.61
Recovery step length	Length of initial step (% body height)	0.60
Toe-off trunk angle	Trunk angle in the sagittal plane at the onset of recovery step toe-off	0.45
Contact trunk angle	Trunk angle in the sagittal plane at the recovery step ground contact	0.66
Full recovery time	Time and steps to reach steady-state walking as defined by the first stride of the group of six strides with an SD below the median SD	0.40

SD: standard deviation; ICC: intraclass correlation coefficient.
[a] ICC were calculated for trails without vibratory stimulation.

vibration) using repeated measures mixed effects models. In these models, first, testing of distribution normality was performed using Shapiro-Wilk *W* test. Then, independent variables of vibration frequency and treadmill speed and their interaction effect were included as within-subject factors and sex as a between-subject variable; post hoc Tukey's honestly significant difference tests were performed for three pairwise comparison between the vibration conditions. Models were repeated separately, once for the ankle and once for the hip stimulation. Main and interactive effects involving vibration condition were our main paramters of interest. As such, main effects of speed on outcome measures were not explicitly reported in the Results. Second, test–retest reliability of the outcomes between the two trials was assessed using intraclass correlation coefficient (ICC), using two-way mixed effects models with an absolute agreement definition [49]. A summary of the results is presented as mean (standard deviation−SD). All analyses were done using JMP (Version 14, SAS Institute Inc., Cary, NC), and statistical significance was concluded when $p < 0.05$.

The sample size estimation was based on detection of changes in balance recovery parameters when participants were exposed to vibratory stimulation. The assumption for sample size estimation was that the effect sizes of changes in timed-up-and-go (TUG) data from previous work would be in the same range for expected changes in balance recovery performance using SVS in healthy young participants. This is based on the fact that TUG performance is shown to be correlated with the balance recovery kinematics [36,41]. Based on changes in postural transitions and turning using vibratory stimulation with frequencies of 40Hz compared to no-vibration conditions (effect size = 0.50–0.80 [36]), a sample of 10 is expected to provide 80% power (2-sided alpha 0.05) to detect a change in balance recovery performance.

3. Results

3.1. Participants

Twenty healthy young participants were recruited. Ten participants were assigned to ankle stimulation (five males and five females, age = 21.5 ± 3.0 years) and 10 were assigned to hip stimulation (four males and six females, age = 22.8 ± 2.5 years). All trials were deemed successful recoveries.

3.2. Balance recovery

Ankle vibratory stimulation elicited main effects on reaction time and recovery step length ($p < 0.002$, Table 3). Reaction time increased by 21.2% on average across the conditions, with no significant difference between 40Hz and 80Hz at the slow speed condition (Fig. 2). Similarly for the fast speed treadmill perturbation, reaction time increased by 24.8% across the conditions, with a significantly greater increase in reaction time for 80Hz frequency in comparison to 40Hz (Fig. 2). Recovery step length increased by 24.7% and 17.7% for slow and fast speed treadmill perturbations, respectively. Significantly larger changes in recovery step length

Table 3
Differences in balance recovery outcomes across three conditions of no-vibration, 40Hz vibration, and 80Hz vibration for the ankle and hip joint.

Ankle Joint Vibratory Stimulation								
	Slow speed			Fast speed			Speed	Frequency
Outcome	No stimulation	40Hz Stimulation	80 Hz Stimulation	No stimulation	40Hz Stimulation	80 Hz Stimulation	p-value	p-value
Reaction time (sec)	0.344 (0.132)	0.418 (0.164)	0.416 (0.146)	0.258 (0.021)	0.266 (0.032)	0.322 (0.073)	<0.0001*	0.0014*
Recovery step length (%)	12.027 (4.872)	14.735 (5.807)	15.255 (4.463)	17.066 (4.729)	19.515 (4.908)	20.644 (5.715)	<0.0001*	<0.0001*
Toe-off trunk angle (deg)	3.867 (2.391)	3.526 (3.122)	4.440 (3.317)	4.716 (2.759)	4.374 (2.095)	5.127 (3.855)	0.0465*	0.2266
Contact trunk angle (deg)	3.947 (2.964)	4.165 (3.261)	5.037 (4.386)	7.222 (4.535)	6.986 (4.032)	7.406 (4.406)	<0.0001*	0.3796
Full recovery time (sec)	1.463 (0.738)	1.179 (0.769)	1.962 (1.438)	1.539 (1.085)	1.611 (1.123)	1.822 (1.036)	0.6272	0.0739
Hip Joint Vibratory Stimulation								
	Slow speed			**Fast Speed**			**Speed**	**Frequency**
Outcome	**No stimulation**	**40Hz Stimulation**	**80 Hz Stimulation**	**No stimulation**	**40Hz Stimulation**	**80 Hz Stimulation**	**p-value**	**p-value**
Reaction time (sec)	0.376 (0.139)	0.392 (0.166)	0.394 (0.163)	0.250 (0.055)	0.265 (0.058)	0.305 (0.133)	<0.0001*	0.3210
Recovery step length (%)	13.393 (4.205)	14.435 (3.813)	13.645 (3.356)	18.017 (4.237)	17.477 (4.269)	17.143 (4.659)	<0.0001*	0.7204
Toe-off trunk angle (deg)	3.902 (1.789)	4.701 (1.796)	4.142 (1.726)	8.118 (2.079)	7.040 (2.345)	7.265 (2.626)	<0.0001*	0.7952
Contact trunk angle (deg)	3.277 (2.545)	3.815 (2.965)	3.864 (2.888)	7.699 (2.163)	6.873 (3.782)	7.738 (4.074)	<0.0001*	0.6706
Full recovery time (sec)	1.155 (1.105)	1.864 (1.517)	2.306 (1.673)	1.395 (1.068)	1.825 (1.249)	1.802 (1.175)	0.6602	0.0188*

were observed for 80Hz stimulation compared to the no vibration condition (Fig. 2). No other balance recovery outcome was significantly influenced by the ankle vibratory stimulation ($p > 0.074$, Table 3).

Hip vibratory stimulation only elicited significant increase in the full recovery time ($p = 0.019$, Table 3). Full recovery time increased by 61.4% for 40Hz and 99.7% for 80Hz vibration for the low-speed treadmill perturbation. Corresponding values were 30.8% and 29.2% for the fast speed treadmill perturbation. No other outcome was significantly influenced by the vibratory stimulation on the hip joint ($p > 0.321$). Of note, all balance recovery outcomes were significantly influenced by the treadmill speed condition ($p < 0.047$), except for full recovery time ($p > 0.627$).

No significant interaction effect of vibration frequency and treadmill speed was observed for any of the balance recovery outcomes ($p > 0.120$). Further, the average ICC across all outcomes was 0.55 ± 0.11, with stronger repeatability values for reaction time, recovery step length, and contact trunk angle (above 0.6) among all outcomes (Table 2).

4. Discussion

4.1. Vibratory stimulation and proprioceptive performance

As hypothesized, the main finding of this study was that local vibratory stimulation on ankle and hip muscles significantly influence recovery performance among healthy young adults. However, unlike our expectation, it was observed that the vibratory stimulation may elicit latency in the reaction response to treadmill perturbation when the stimulation was applied to ankle muscles. This was observed by more than 20% increase in the initiation of the recovery stepping when the stimulation was applied to ankle sites. On the other hand, full recovery time from treadmill perturbation was influenced by vibratory stimulation when it was applied to hip muscles. These alterations were evidenced based on more than 30% increase in required time for the full recovery from perturbation and achieving stead-state walking. These alterations suggest an overall delayed recovery performance when the vibratory stimulation is applied to muscle spindles in healthy young participants. This observation was in agreement with our previous findings, where a deterioration in upright balance performance, represented by larger sway, was reported for healthy young individuals when vibratory stimulation was applied to ankle muscles [42]. Other studies on upper-extremity movement in healthy young participants showed similar adverse effects of vibratory stimulation, which were recorded by overestimation of the actual displacement or velocity of the elbow [43]. Furthermore, distortion of static joint angle and movement perception and increased systematic errors in the end point of movement of the biceps brachii due to tendon/muscle vibration were reported [44]. All these experiments suggest that vibratory stimulation may influence muscle spindle performance, which has been implemented in the current study to investigate the proprioceptive role of ankle and hip muscles in balance recovery from tripping.

4.2. Ankle vs. hip vibratory stimulation

Current findings suggest that the location of stimulation may impact the vibration induced alterations in balance recovery performance. While the reaction time and recovery step length significantly increased by ankle muscle stimulation, no significant change in these outcomes was recorded with hip muscle stimulation. One explanation for this observation may be the fact that proprioceptive information comes from the ankle muscles provides the most contribution in balance recovery performance. Although previous studies showed that ankle rotation possibly could be detected through proprioception of other lower extremity joints including the hip and/or knee joints [45], it was shown that ankle proprioceptive stimulation altered both postural and dynamic components of balance in healthy participants [46]. In these studies, dynamic balance was measure using stabilizing and destabilizing forces. In agreement to these findings, for the first time, we showed that ankle proprioceptive information also plays the more important role during balance recovery from treadmill perturbation compared to the hip joint among healthy young individuals.

Observed differences between ankle and hip stimulation may be also related to the mechanism implemented for the recovery (ankle vs. hip). Previous work suggested that hip muscles play more important role than ankle muscles for recovery from larger perturbations in the frontal plane (forces applied medially or laterally to a stance leg) during slow treadmill walking [47]. All participants within the

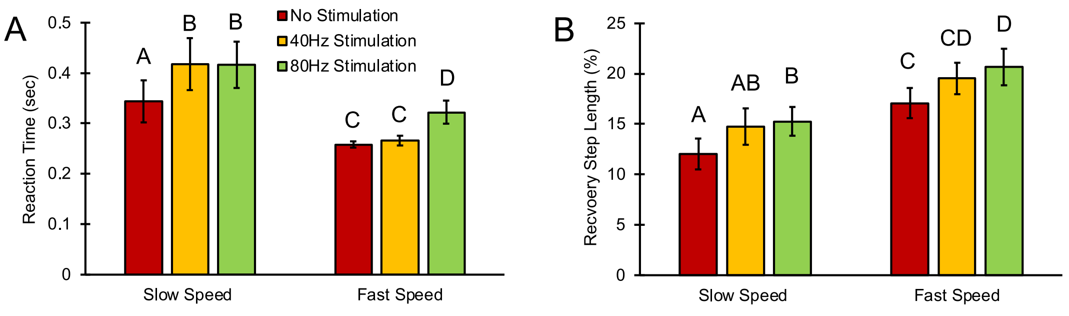

Fig. 2. Changes in balance recovery outcomes using vibratory stimulation on the ankle joint. 2A: Change in reaction time; 2B: Change in initial recovery step length. Tukey's differences in balance recovery outcomes across vibration frequencies are presented using different alphabets (A, B, AB, C, D, and CD).

current study were able to successfully recover from the perturbation without using the harness. This suggests at the implemented level of perturbation, ankle muscles and proprioceptive information from these muscles may have been the main source of adjustment to perturbation. Further, although no significant difference in reaction time and recovery step length was observed when vibration was applied to hip muscles, full recovery time significantly increased in this vibration condition. Accordingly, hip muscles may contribute to balance refinement after the recovery stepping; however, this hypothesis should be confirmed in future research. These findings suggest that proprioceptive information from ankle muscles plays important role in recovery initiation from perturbation, while the proprioceptive information from the hip muscles may help with full recovery performance in response to perturbation.

4.3. Impact of vibration frequency and perturbation level

Previous evidence suggests that in healthy persons, 80Hz vibrations of ankle muscles produce the maximal effect on upright standing postural balance, and in frequencies below 40Hz the vibration effects may be smaller and inconsistent among individuals [32–34]. Current results also indicated that, in general, higher frequency of 80Hz caused more impact on dynamic balance performance compared to lower frequency of 40Hz, especially within more difficult level of perturbation. Although the interaction effects between vibration frequency and treadmill speed was not significant ($p > 0.12$), as it is demonstrated in Fig. 2, the effect of vibration frequency on changes in balance recovery performance may be influenced by the level of perturbation difficulty. The observed behavior may occur because healthy young individuals use different dynamic balance strategies (ankle vs. hip) for different difficulty level of perturbations. Therefore, even a low frequency vibration may noticeably impact balance recovery performance in low-speed treadmill perturbation where the ankle proprioceptive information is critical for balance recovery. Nevertheless, this hypothesis needs to be confirmed in future research.

Although the focus of the current study was to investigate the effect of vibratory stimulation on balance recovery, significant differences in balance recovery outcomes were also observed at different treadmill perturbation speeds. Current findings showed that following the perturbation, balance recovery was initiated with a recovery step, which was significantly larger (32%) on average across fast speed treadmill perturbation compared to lower speed (Table 3). In higher speed of treadmill perturbation, the reaction time was also significantly reduced (29%, Table 3). Because perturbation at higher treadmill speed requires more intense balance configuration, a shorter reaction time and larger recovery step occurred to maintain dynamic balance in this condition. It is expected that faster treadmill movements cause faster and larger changes in ankle angle, which may consequently lead to ankle muscles faster reaching the level of detection of position/velocity changes. Further, we observed that toe off and heel contact trunk angles were significantly larger (49% and 82%, respectively) for faster speed treadmill perturbation compared to slower speed, during the recovery stepping (Table 3). The observed difference in the trunk angle during the balance recovery process may occur due to different balance recovery mechanism employed at different perturbation difficulties. Previous studies showed that ankle muscles are heavily involved in non-stepping balance recovery at lower intensity perturbation, and the contribution of hip muscles increases at a higher intensity perturbation [2]. The increased trunk angle during toe-off and heel strike at higher speed of treadmill perturbation may also confirm an increased contribution of hip muscles at a more challenging balance recovery performance involving recovery stepping. Lastly, it was observed that the only outcome that was not significantly influenced by speed was full recovery time. This may be due to increase in reaction time and recovery step length at higher treadmill speed perturbation, which suggest that healthy young individuals can successfully recover in similar durations from different level of perturbation difficulties.

4.4. Clinical implications

The balance recovery behavior and the influence of vibration, as has been observed in previous work, may be different between young and older adults. We previously showed that vibratory stimulation has opposite impact on healthy young participants versus high fall risk older adult, during upright standing postural balance. In older adults, proprioceptive signal deterioration occurs because of nerve cell death and demyelinating process with aging [48,49]. This signal deterioration, to some extent, can be compensated by applying random low-intensity noise (vibratory stimulation), which produces the effect of so-called stochastic resonance [50–52]. So, we hypothesis that in dynamic balance performance the level of alterations in proprioceptive afferent signal using vibratory stimulation depends on proprioceptive deficits and vibratory stimulation may enhance balance recovery performance among high fall risk older adults with proprioceptive deficits. In addition to previous literature, current findings, for the first time, provided evidence that vibratory stimulation can influence balance recovery from tripping within a treadmill setup perturbation in healthy young participants. In future, we will investigate the impact of vibratory stimulation on balance recovery performance among older adults at different level of fall risk categories. Continuation of these series of studies will potentially lead to establishing a comfortable wearable platform to immediately improve proprioceptive deficits in older adults, with the goal of reducing the number of preventable falls and promoting healthy aging among the ever-growing older adult population.

4.5. Limitations and future direction

Due to some limitations, findings from the current study should be interpreted cautiously and further confirmations are required. We investigated the impact of vibratory stimulation on ankle and hip muscles; however, the proprioceptive information from sole muscle also plays an important role on dynamic balance performance [53]. In our future studies we will investigate the impact of sole vibratory stimulation on balance recovery. In the current study, the goal was to provide evidence of balance recovery alterations due to ankle/hip muscle stimulation during trip recovery. Nevertheless, the contribution of each muscle (e.g., gastrocnemius as the ankle plantar flexor vs. tibialis anterior as the ankle dorsiflexor), as well as side of the exposed stimulation (e.g., recovery vs stance leg) should be investigated in the future research. These effects should be further investigated during slip recovery as another major circumstance leading to fall. Further, as mentioned before, in this study the selected treadmill speeds were not high enough to make healthy young adults to fall or require high level of effort to control the balance. Accordingly, we were unable to see how vibration adversely affects balance recovery during more challenging conditions, and overall balance recovery ability. Further, as a result of relatively lower speed perturbation, the effect of hip proprioceptive involvement on controlling balance may not be tested accurately in this study. We suggest testing higher speed for healthy young adults to make the perturbations more difficult to better investigate the effect of hip proprioceptive information on dynamic balance.

5. Conclusions

Current findings provided evidence that vibratory stimulation can affect the balance recovery performance among young adults and the results depends on the area of stimulation (ankle vs hip). Within our sample of healthy young adults, vibratory stimulation caused a negative impact on the balance recovery performance, which was observed as a delayed reaction time when the stimulation was applied to the ankle muscles. Further, vibratory stimulation of the hip muscles delayed the full recovery process from the treadmill perturbation. Current results suggest that reaction time, recovery step length, and trunk angle at the first heel strike provide good (0.60–0.75 ICC) and trunk angle at the toe off during the recovery stepping and the full recovery time provide fair (0.40–0.59 ICC) repeatability for assessing balance recovery performance.

CRediT authorship contribution statement

Mehran Asghari: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Karam Elali:** Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alexis Sullivan:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Bonnie LaFleur:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Michael L. Madigan:** Conceptualization, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nima Toosizadeh:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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