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Quantifying Effects of Perturbation Intensity on Slip Outcome in Young Adults

A THESIS

Submitted to the Department of Kinesiology and Health in the College of Education and Human Development, Georgia State University

In partial fulfillment of the requirements for the degree of Master of Science in Exercise Science

By

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Abstract

Motorized treadmills have been widely used to examine the reactive balance control of the human body after an external perturbation, like slips or trips, and develop perturbation-based interventions for preventing falls. The treadmill-induced perturbation profile depends on the belt's duration, velocity, acceleration, and displacement. The intensity of the perturbation is affected by these interrelated factors. There is a lack of consensus regarding how to choose the perturbation intensity. One prerequisite condition to bridge this knowledge gap is to examine how the perturbation intensity affects its outcome. The purpose of this study was to quantify how the slip intensity, characterized by the belt's peak velocity (low intensity: 0.9 m/s; medium intensity: 1.2 m/s, or high intensity: 1.8 m/s), affects the slip outcome (fall or recovery) in young adults while the slip distance is controlled. Specifically, it was hypothesized that, in comparison with a low intensity, a high slip intensity would lead to 1) a greater risk of a slip-fall and 2) a shorter recovery step latency, longer slip distance, and larger hip descent after the slip onset. Thirty-one healthy young adults aged 18 to 45 years were enrolled and randomly assigned into three groups with different peak slip speeds: low (0.9 m/s), medium (1.2 m/s), and high (1.8 m/s). After the warmup, participants stepped on the ActiveStep treadmill. Following five standing trials without slips, all subjects experienced an unexpected slip perturbation induced by the treadmill with the assigned peak slip velocity. The slip displacement was the same for all groups at 0.36 m. A motion capture system collected participants' full-body kinematics. The slip outcome (a binary variable: fall or recovery) was determined by the hip descent after the slip onset. The faller rate was the primary outcome variable. The secondary outcome measures included the continuous measurements of the hip descent, dynamic stability, and slip distance at the instant of recovery foot liftoff, and the latency of the recovery step. The outcome measures were compared among groups using χ^2 or one-way analysis of variance followed by appropriate post-hoc tests to test the hypotheses. The results overall support the hypotheses. Specifically, individuals in the high-intensity group fell significantly more than the other two groups. Additionally, they were less stable with a longer slip distance at liftoff than their peers in the lower intensity groups. This study could guide the selection of slip profiles for future studies that use perturbation as a test platform or interventional paradigm.

Keywords: fall prevention, dynamic stability, slip intensity

Table of Contents

Introduction

Falls are a severe healthcare problem in older adults and people with neurological diseases (Delbaere et al., 2010; Homann et al., 2013; Rubenstein, 2006). Even in protective environments, such as hospitals, falls and resulting hazardous fractures are reported as a significant concern (Zhang et al., 2018). The number of older adults who sustained a fall-related injury drastically increased by about 268% (from 5,622 to 21,574), and the fall-induced death rate elevated by about 31% from 2007 to 2016 (Burns and Kakara, 2018; Kannus et al., 1999). Slips account for up to 40% of all falls in older adults from outdoor activities (Crenshaw et al., 2017; Yang, 2016). According to a previous study, fall-related fractures caused by outdoor slips on ice and snow surface increased among older populations in winter when compared with other seasons (Bulajic-Kopjar, 2000). Thus, it is necessary to develop strategies for preventing falls.

Most of the extant fall prevention interventions target modifiable risk factors, such as muscle weakness, balance deficits, vision impairments, medication management, home-environment modification, etc. (Keay et al., 2015; Moncada, 2011). Although these interventions have shown positive effects on reducing falls in older adults, they do not address the need to recover balance quickly from an external perturbation. For example, following a balance loss after a perturbation (such as slips or trips), one must quickly react to the balance loss and adjust the body movements. The majority of the current exercise- or balance-based training paradigms do not involve the context of perturbation, but unperturbed motor tasks, like walking and standing, which fail to follow the task-specificity training principle and may render the training effects suboptimal.

Perturbation training has recently emerged as one of the encouraging interventions preventing falls, which reflects the task-specific principle (Gerards et al., 2017; McCrum et al., 2017). Perturbation training exposes trainees to unexpected disturbances during regular motor tasks (such as walking or standing) and can enhance the human body's reactions to external disruptions by executing effective recovery steps and/or arm swing movements. Various types of approaches have been used to create perturbations. For example, some studies used the oil-contaminated vinyl surface to produce slips (Cappellini et al., 2010; Chou et al., 2001; Chou et al., 2000; Lee-Confer et al., 2022; Liu and Lockhart, 2009; You et al., 2001). The aluminum rollers were also used to initiate a slip (Marigold and Patla, 2002). Despite being useful in producing slips, these approaches have a limitation: they cannot control the intensity of the slip perturbation, which may introduce biases to the findings. To overcome this limitation, treadmill-based slip training during gait or standing has also been broadly used to train various populations and reduce their fall risk (Pai et al., 2014; Yang, 2016; Yang et al., 2018a; Yang and Pai, 2013) or to examine the reactive balance control responding to external perturbations (Espy et al., 2010b; Kajrolkar et al., 2014; Yang et al., 2016; Yang and Pai, 2013; Yang et al., 2019).

One of the popular treadmills used for perturbation training-related research is the ActiveStep treadmill (Simbex, NH) (Simpkins et al., 2022; Sung et al., 2021; Yang et al., 2022; Yang et al., 2013; Yang et al., 2018b; Yang et al., 2019). The slip perturbation is induced by suddenly accelerating the belt forward during walking or standing. After the rapid anterior movement of the feet or the base of support (BOS), the trunk falls backward, mimicking a slip-initiated movement. The ActiveStep treadmill has been used in various populations, including people with multiple sclerosis, stroke, obesity, lower back pain, and professional ballet dancers, during different motor tasks, such as slips, trips, and walking on split-belts with different speeds (Crenshaw et al., 2019; Dusane and Bhatt, 2021; Simpkins et al., 2022; Sung and Hosmer, 2021; Yang et al., 2017; Yang et al., 2019).

One of the key parameters for perturbation training is the perturbation intensity. However, there is a lack of consensus about how to select the perturbation intensity. No study has quantified how the intensity affects perturbation outcome, although it is intuitive that a higher intensity would lead to a greater risk of falling. The unclear understanding of the impact of the intensity on slip outcome is not a trivial issue, as it may hinder the further applications of treadmill-based perturbation protocol. Given that the slip intensity may have a significant impact on the reactions to and outcome of the perturbation, it is imperative to quantify the relationship between slip intensity and outcome.

Therefore, the primary purpose of this thesis project was to examine how the slip intensity, characterized by the peak belt velocity while the slip distance is controlled, affects the slip outcome (fall or recovery) and other reactive balance metrics, including dynamic stability, recovery stepping, and slip distance. Given its exploratory nature, this project focused on young adults exposed to an unexpected slip during standing on the ActiveStep treadmill. Participants experienced one of the three slip intensities (0.9, 1.2, and 1.8 m/s of the peak belt speed). Their reactions to the slip were compared between groups to elicit the possible impact of slip intensity on the perturbation outcomes.

Statement of Question

The research question of this thesis project is how the slip intensity, characterized by the belt's peak velocity, affects the slip outcome (fall or recovery) and other slip-reaction variables in young adults during standing while the slip distance is controlled. To address this question, three slip intensities (0.9 m/s, 1.2 m/s, and 1.8 m/s) were used, while the slip distance was preset at 0.36 m. This project would extend our understanding of how slip intensity determines slip outcome.

The gained information could inform the selection of slip profiles for future studies that use perturbation as a test platform to quantify reactive balance, a novel way to identify the mechanisms of falls, or interventional paradigms to reduce falls in various populations at high fall risk.

Rationale

Despite the increasing application of slip-based perturbation (Gerards et al., 2022; Kajrolkar et al., 2014; Mansfield et al., 2015; Yang, 2016; Yang et al., 2009; Yang et al., 2018a; Yang and Pai, 2013; Yang et al., 2019), no study has quantified how the intensity affects the slip outcome. The lack of such information could present a barrier to increasing the application of perturbation-based paradigms in rehabilitation. Therefore, it is vital to study the relationship between slip intensity and the reactions to slips. A sound understanding of this relationship could provide valuable guidance in designing effective fall prevention programs or selecting appropriate slip profiles to examine reactive balance control.

Hypothesis

Corresponding with the overall purpose, it was hypothesized that:

(1) The high slip intensity would result in a large risk of falling after a standing-slip in young adults. Specifically, a higher slip intensity will induce more falls than a lower intensity during standing in healthy young adults.

(2) An increased slip intensity would make the responses to the slip perturbation less effective in healthy young adults following an unexpected standing-slip. Specifically, a higher slip intensity will make participants less stable with a shorter step latency, a

longer slip distance, and a larger hip descent than a lower intensity during standing in healthy young adults.

Delimitations and Limitations

Delimitations

This study had two delimitations. First, healthy young adults aged 18 to 45 were recruited. The findings of this study might show different trends in overall outcomes (i.e., dynamic stability, fall rate, etc.) for other populations, including older people and patients with neurological diseases. Second, only the standing slip was adopted in this project. The standing-slip protocol may not reflect the reactions to a gait slip as walking is a continuous and dynamic motor task while standing is a static task (Yang et al., 2009). However, the findings of this project will provide valuable information to design new studies to expand these two delimitations.

Limitations

This study was associated with several limitations. First, all participants were barefoot, which may differ from the everyday living conditions where individuals wear shoes. Therefore, the shoe sole's effect on the reactive balance control was not considered in this study, and the results may not reflect real-life situations. Second, only slip perturbation was used for participants, although other types of external perturbation could also cause falls. Slips represent a major reason for falls in older adults (Burns and Kakara, 2018; Yang, 2016). Therefore, the findings of this project could still be meaningful. In addition, the results of this project could provide useful information for designing future projects that focus on the effect of perturbation intensity on the trip outcome. Third, only three slip intensities (peak belt velocity: 0.9, 1.2, and 1.8 m/s) were utilized in this study. Although the belt velocity between 0.9 m/s and 1.8 m/s might be effective in training people to maintain dynamic balance and prevent falls and has been used in previous studies (Simpkins et al., 2022; Sung et al., 2021; Yang et al., 2017; Yang et al., 2019), they only represent a small portion of the countless numbers of peak belt speeds. Last, participants of this study were exposed to slips in a laboratory environment. It is unknown whether the findings of this study can be transferred to everyday life situations. Hence, the generalization of the findings to real life is unclear. Further large-scale studies with large and diverse sample sizes are needed to address these limitations.

Definitions

In this study, the following terms were defined and used:

- Base of support (BOS): the contact area between the feet and the belt surface.
- Center of mass (COM): the weighted average position of all body segments.
- Dynamic stability: a measurement of the body's fall risk level by considering the kinematic relationship between the body's COM and its BOS.
- Feasible Stability Region (FSR): the collection of all possible COM motion states which can maintain a balanced upright body posture without changing the BOS on the COM velocity-position phase space. Two limits enclose this region: the limit against backward falling and the limit against forwarding falling.
- Liftoff (LO): the time instant at which the recovery foot separates from the treadmill belt surface after the slip occurrence.
- Perturbation: a disturbance or disruption exerted unexpectedly to normal human locomotion or posture.

- Recovery step: the first backward step following the onset of the slip taken by a participant to attempt to restore the body's balance.
- Slip distance: the moving distance of the belt between the instants of ON and LO. It was be normalized by body height.
- Slip onset (ON): the instant when the belt marker's anteroposterior position is at least three standard deviations above its baseline value.
- Step latency: the time duration between ON and LO.

Review of Literature

Falls and Resulting Injuries

Falls are a serious concern facing older adults and people with movement disorders (Boonsinsukh et al., 2012; Burns and Kakara, 2018; Crenshaw et al., 2017). About 1/3 of older adults fall at least once a year (Gill et al., 2005; Hausdorff et al., 2001b), and the risk of falls in people with movement dysfunctions is even higher (Bloem et al., 2004; Homann et al., 2013; Wilczyński et al., 2021). Falls lead to injuries (such as bruising, fractures, and traumatic brain injury) and even death (Delbaere et al., 2010; Fu et al., 2017; Homann et al., 2013). The consequence of falling could affect mental symptoms such as trauma, fear of falling, and anxiety. For instance, the fear of falling and cognitive decline may mainly interfere with recovery from a pelvic fracture after surgical treatment (Voshaar et al., 2006), and general anxiety symptoms are also associated with the high risk of falling (Hallford et al., 2016). Additionally, fallers would exhibit a passive attitude toward the environment during the recrudescence of falls, not to reencounter falls. Following their reduced outdoor activities, their physical functions, such as muscle strength and balance, would be decreased with diminished interpersonal relationships. Degraded functional movements need healthcare support, leading to economic burdens for individuals and the government. By 2030, the estimated medical costs for treating fall-related fatal and non-fatal injures for older fallers were projected to be $101 billion (Florence et al., 2018). It is thus necessary to develop to reduce the risk of falls in elderly people.

Fall Prevention Interventions

Given the costly consequences of falls, it is critical to develop programs for preventing falls. Considerable efforts have been dedicated to designing fall prevention regimes, and various programs have been established (Choi and Hector, 2012; Day et al., 2015; Haines et al., 2009; Inokuchi et al., 2007; Irez et al., 2011; Lee and Yu, 2020; Li et al., 2005; Logghe et al., 2009;

Vlaeyen et al., 2015). The developed fall prevention programs for older adults are based on single and multifactorial interventions; single intervention is generally focused on the individual's specific information to modify the potential risk factors or medications (Choi and Hector, 2012).

Unlike the single intervention, multifactorial interventions, including customized programs, comprehensive medical exams, activities of daily living, cognition assessments, nutrition assessment, and gait stability training, were conducted for at least six months with medical professionals (Choi and Hector, 2012; Lee and Yu, 2020; Vlaeyen et al., 2015). In the multifactorial intervention program, regular partial or whole body exercise (i.e., lower limb-strengthening exercise, Tai Chi, Pilates, etc.) has been used as the core for older adults under supervision, which can help to improve balance and coordination functions (Day et al., 2015; Haines et al., 2009; Inokuchi et al., 2007; Irez et al., 2011; Li et al., 2005; Logghe et al., 2009). For example, exercise training with strategies for improving vision and sensation was tested in older adults over 75 years (Lord et al., 2005).

Dynamic Stability Theory

The small base of support (BOS), high position of the center of mass (COM), and multi-segment structure make the human body highly and naturally unstable. Balance is preserved during a static task, like standing, when the COM's projection is confined within the BOS (Fig. 1.a). However, static stability limits are not applicable to dynamic tasks (Yang, 2016). For example, at liftoff during walking, the COM's projection on the ground is always behind and outside the BOS, defined as the leading foot-ground contact area. According to the static stability limit, a person should encounter a backward balance loss in this scenario, which does not materialize in reality. Therefore, a different metric must be utilized when considering dynamic conditions.

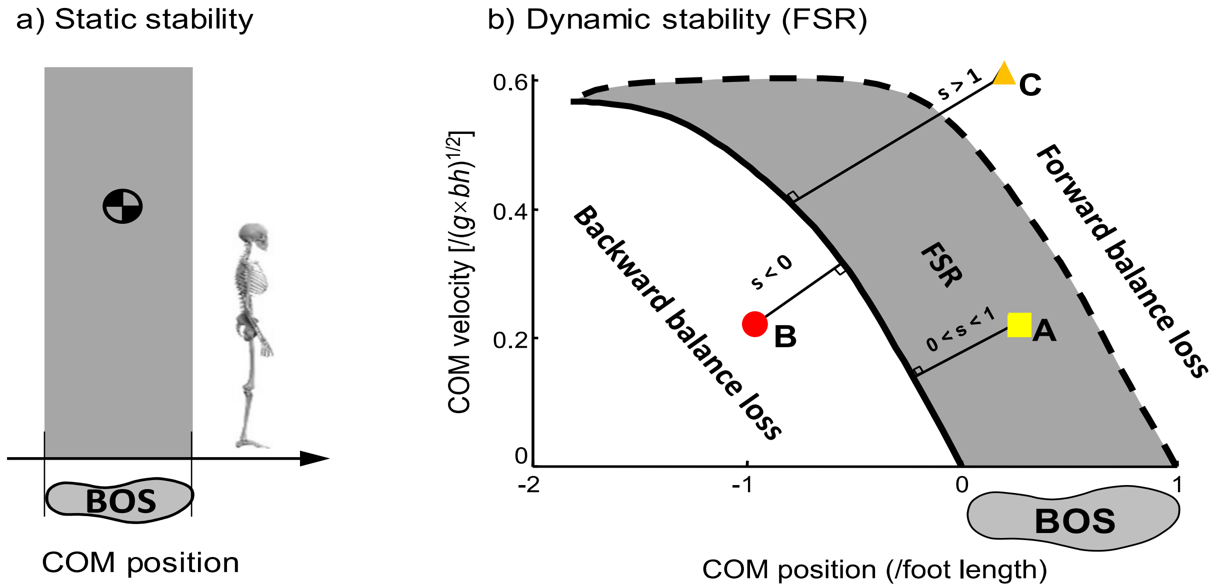

Fig. 1. Schematic illustration of a) static stability and b) Feasible Stability Region (FSR) theory. The static stability is governed by the COM position and the BOS. When the COM's projection is located in the BOS, a person is stable, as demonstrated by the shaded region. Dynamic stability is defined by the FSR theory using the position and velocity of the COM relative to BOS. When the COM motion state is within the FSR limits (A), balance can be maintained without changing the BOS. A COM motion state below/above the lower/upper FSR limit indicates instability against backward/forward balance loss (B/C). Dynamic stability (*s*) is calculated as the shortest distance (solid lines) from the COM motion state to FSR's lower limit.

Several dynamic stability theories have been proposed to evaluate the risk of falls: the Feasible Stability Region (FSR) framework, Marginal of Stability (MoS) constructure, Lyapunov exponents, and the Floquet multiplier. Both the FSR (Yang et al., 2007) and the MoS (Hof et al., 2005) frameworks characterized the kinematic relationship between the body's COM and BOS. The motion state (i.e., the position and velocity) of the COM relative to the BOS is used to quantify dynamic gait stability. Given that FSR is derived based on an asymmetric 7-link walking model (Yang et al., 2007) while the MoS concept was established on a highly simplified

2-link symmetric human model (Hof et al., 2005), FSR theory can more accurately assess dynamic stability than MoS.

Alternatively, variability of gait parameters has also been applied to quantify a person's stability. Based on the nonlinear dynamics theory for cyclical movement, kinematic variability is indicative of stability (Dingwell et al., 2001; England and Granata, 2007; Hausdorff et al., 2001a). Indices, such as the maximum Floquet multipliers (Dingwell et al., 2007) and Lyapunov exponents (Dingwell and Cusumano, 2000), have been employed to analyze continuous joint or trunk kinematics (Bruijn et al., 2010; Dingwell and Kang, 2007) to respectively evaluate body's orbital and local stability. Further, simpler yet, descriptive spatiotemporal gait parameters such as the standard deviation of step length, step width, or step/stride time can also yield meaningful information regarding a person's control of gait stability (Hausdorff et al., 2001a; Owings and Grabiner, 2004; Woledge et al., 2005). However, all variability-based metrics are less effective in predicting slip-related falls than the FSR-based stability measurement (Yang and Pai, 2014). One potential reason could be that they did not directly account for the dynamic mechanisms underlying the variability (Beauchet et al., 2007). A dynamic system, especially a human body, can be described as a complex neuro-controller coupled with a nonlinear biomechanical system. Limit-cycle behavior generated by this system is influenced by input disturbances causing output variance. In this study, FSR theory was used to calculate dynamic stability instead of other approaches.

The FSR theory simultaneously considers the COM position and velocity relative to the BOS (Yang, 2016; Yang et al., 2007, 2008a). When the COM motion state is within the FSR (Fig. 1.b, point A), a person can maintain body balance without changing the BOS. When the COM motion state is behind the lower limit of the FSR (Fig. 1.b, point B), forward momentum is insufficient to move the COM over the BOS, leading to backward balance loss. When the COM motion state is above the upper limit of the FSR (Fig. 1.b, point C), the COM has disproportionate forward momentum, which would carry the COM outside the toe of the BOS. A forward recovery step is necessary to avoid falling forward.

Determined as the shortest distance from the COM's motion state to the lower limb of the FSR, dynamic stability (Fig. 2.b, solid lines) has been used to quantify fall risk in both healthy and pathological populations during walking, standing, and sit-to-stand tasks under unperturbed or perturbed conditions (Ahn et al., 2022a, 2022b; Bhatt et al., 2011; Bhatt et al., 2013; Kajrolkar et al., 2014; Liu and Yang, 2017; Mak et al., 2011; Simpkins et al., 2022; Wang et al., 2011; Yang et al., 2022; Yang et al., 2009; Yang et al., 2018a; Yang and Pai, 2013, 2014; Yang et al., 2008b; Yang et al., 2018b). Recently, dynamic stability has been closely related to the fall risk during standing in young adults (Simpkins et al., 2022). The FSR-based dynamic stability provides a novel metric to assess the risk of falls. It can be used to investigate the effects of slip intensity on perturbation outcomes.

Perturbation-based Training and Assessment

The complex balance maintenance process results from three essential sub-systems: vision, proprioception, and the vestibular system (Woollacott and Shumway-Cook, 1990). These sub-systems coordinate with each other to share the sensory information within a specific short term; then, the subsequent motor reaction should be amended to maintain the balance. The impairment of any systems, however, could deteriorate the quality of information to delay the decision to move the COM of the body to catch up with the perturbed BOS. The perturbation-based training has been used to improve stabilizing ability against external repeated perturbations, such as slips, trips, and others. Stability improvement is associated with motor control and motor adaptations, including the predictive and reactive to collapses. The previous experience of sudden perturbation could enlarge the expectation of the movement of locomotors leading to the reduction of perturbation impact and the level of the recovery response. Reactive adaptation is the response to unexpected perturbations: earlier perturbation detection and faster recovery steps (McCrum et al., 2022). This adaptation enhances the decision to move the body's COM into the perturbed BOS in order not to lose balance. Several studies involved healthy older adults, older adults with a high risk of falling, Parkinson's disease, and multiple sclerosis patients.

Perturbation has also been used as a way to produce standardized falls to either assess one's reactive balance or test the effectiveness of a fall prevention intervention. In the literature, the majority of the relevant studies adopted a self-reported approach to gathering fall-related data (Ehrlich et al., 2019; Huang et al., 2017; Lai et al., 2020). However, the self-reported approach has inherent critical shortcomings (Von Stengel et al., 2011). First, the self-report method is subject to inaccuracy, bias, and omission, decreasing the reliability of data on fall incidence (Al-Qazzaz et al., 2014; Cummings et al., 1988; Jenkins et al., 2002). Up to 32% of falls may be unreported over 3 months (Cummings et al., 1988). Second, the self-report method does not account for activity level and exposure to the risk of falling, factors that can affect the likelihood of falling and may lead to underestimated actual fall rates (Graafmans et al., 2003; Gregg et al., 2000; Peeters et al., 2010; Wijlhuizen et al., 2010). There might be a U-shaped relation between fall incidence and activity, with the most inactive and the most active being most at risk of falling (Graafmans et al., 2003; Gregg et al., 2000; Lu et al., 2020). Those who are the least active may have the least exposure to conditions that might induce falls but also have a high risk of falling when exposed, while the most active have high exposure but a low risk of falling. Regardless of the specific shape of the association between fall exposure and fall incidence, activity or some other surrogates for fall exposure must be quantified in addition to the number of falls if fall risk/exposure is the outcome of interest rather than fall risk/time (Wijlhuizen et al., 2010).

Third, self-reported data often lack information on the accurate occurrence time and specific details of the actual falls (Feldman and Robinovitch, 2006; Feldman et al., 2010; Yang et al., 2015), which could vary considerably from person to person. Without considering or controlling for the time and level of exposure to the risk of falls, it is very difficult, if not impossible, to precisely investigate the effect of any treatments on reducing real-life fall rates. Last, issues with the self-report method and the relative infrequency of falls usually necessitate large sample sizes to detect significant reductions in fall incidences from interventions. Following these large samples over a long period of time results in high costs per study; thus, fewer studies can be funded to evaluate fall-reduction interventions. The only way to truly quantify the training effect and fully control for exposure to the risk of falling is to evaluate how subjects respond to identical gait perturbation administered in controlled laboratory conditions. Treadmill-based perturbation serves as a novel solution to this requirement, partially contributing to the popular application of perturbations.

Slip Perturbation as a Tool to Assess Reactive Balance Control

Slip perturbation has also been used as a new way to assess the human body's reactive balance control and identify the mechanisms of falling after an external perturbation (Kajrolkar et al., 2014; Simpkins et al., 2022; Simpkins and Yang, 2023; Sung et al., 2021; Yang et al., 2018a; Yang et al., 2018b). The traditional clinical balance tests (i.e., Timed-Up-and-Go (TUG) and Berg Balance Scale Test (BBS)) can reach only about 65% accuracy in predicting falls in healthy older adults (Bhatt et al., 2011; Greene et al., 2010). These conventional balance assessments are based on volitional body movements but do not consider how the body reacts to unexpected perturbations, which present the major cause of falls in older adults (Simpkins and Yang, 2022). This explains why the traditional balance assessment may be less powerful in predicting falls. On the other hand, perturbation-based reactive balance measurement has been used as a novel way to assess fall risk and predict falls (Sung et al., 2021; Yang et al., 2018a; Yang et al., 2016; Yang and Pai, 2013; Yang et al., 2019).

Slip perturbation has recently been used to assess the risk of falling for patients with impaired somatosensory function and reaction control against the slips instead of the conventional clinical assessment models. For example, a previous study indicated that slip-based reactive balance assessment could achieve a higher prediction accuracy of falls in older adults (Yang and Pai, 2014). Another study reported that people with stroke experience a much higher likelihood of falling (41%) than their healthy counterparts (16 %) after a standardized slip perturbation (Homann et al., 2013). The other study revealed that the repeated slip perturbation could enhance the reactive response reducing the fall incidence in patients with multiple sclerosis as individuals with multiple sclerosis showed a significant reduction in the fall rate on the first slip (92.3%) to the last slip (30.8%, $p = 0.007$) (Yang et al., 2019).

The slip intensity varied drastically among previous studies. For instance, a previous study found that obese people had impaired balance control functions when exposed to the unexpected standing-slip perturbation preset as 2.4 m/s of peak slip velocity and 12 m/s^2 of slip acceleration (Yang et al., 2017). Another study utilized the perturbation intensity characterized by 0.12 m/s of slip velocity for 0.625 m of slip displacement to alter the body balance strategies for patients with lower back pain (Sung and Hosmer, 2021). The study which investigated the progressive intensity of treadmill gait-slip training for chronic stroke patients was set up with the slip intensity consisting of six levels: fixed acceleration of 3 m/s^2 and six levels for the slip distance: 1.5, 3.37, 6, 9.37, 13.5, and 18.37 cm, respectively (Dusane and Bhatt, 2021). A recent study has demonstrated that the slip intensity profile characterized by 0.16 m of slip distance, 1.6 m/s of peak slip velocity, and 8 m/s^2 of slip acceleration was effective in acquiring the ability against slip-related falls using repeated slip perturbation in multiple sclerosis patients (Yang et al., 2019).

Despite the wide use of treadmill-based slip perturbation in various populations and settings, it remains unclear how to appropriately select the slip profile in order to maximize the training effect, accurately assess the reactive balance control, and evaluate the efficacy of fall prevention programs. To address these questions, it is essential to clearly understand how slip intensity determines slip outcome and the reactive responses to slip perturbation. However, no study has been conducted to quantitatively assess how slip intensity affects slip outcome. Therefore, there is a need to clarify the relationship between slip intensity and slip outcomes.

The primary purpose of this study was to quantify how slip intensity, characterized by the peak belt speed, affects the body's reactions to perturbation. Three levels of intensity were adopted, and participants' responses to the slip were recorded and compared between levels. The comparisons could provide insight into the effects of slip intensity on reactive balance control. The findings from this study could guide the slip intensity selection for future slip-based studies.

Methods

Participants and Study Design

This study recruited thirty-one healthy young adults aged between 18 and 45 years (Table 1). To be enrolled, participants should not have any acute or chronic neurological and musculoskeletal diseases and a history of lower extremity injuries in the past three months. The process, purpose, and potential risks during data collection of this study were thoroughly explained to participants before obtaining their written consent. Qualified participants were assigned randomly into three groups based on the slip intensity: group A (or low intensity group, 0.9 m/s), group B (medium intensity, 1.2 m/s), and group C (high intensity, 1.8 m/s), respectively. All participants experienced an unannounced slip during standing with the assigned intensity on the ActiveStep treadmill. Their responses to this slip, characterized by the slip outcome (fall or recovery, primary outcome), dynamic stability, recovery step latency, hip descent, and slip distance at recovery foot liftoff (secondary outcome), were compared between groups to test the hypotheses. This study was approved by the Institutional Review Board of Georgia State University (Protocol #: H20734).

Table 1. Comparison of demographic information in mean ± standard deviation among three groups.

Group	A (0.9 m/s)	B (1.2 m/s)	C (1.8 m/s)	*p*-value
Number	10	11	10	
Sex (M/F)*	4/6	2/9	4/6	0.462
Age (years)	26.10 ± 4.95	22.60 ± 3.41	26.20 ± 4.89	0.489
Height (m)	1.70 ± 0.11	1.66 ± 0.08	1.69 ± 0.07	0.853
Mass (kg)	79.51 ± 18.96	68.6 ± 9.72	73.84 ± 16.45	0.651

M: male; F: female.

*: χ^2 test was used.

Procedure

All data collection sessions were carried out in the Biomechanics Laboratory at Georgia State University, Atlanta, Georgia. Before participant arrival, all instruments and equipment were calibrated to ensure the accuracy of data collection. All participants received the instruction to avoid exercise, which can cause muscle fatigue since it could display the delayed muscle reaction time during the slip perturbation.

Upon arrival, participants received a verbal explanation of the study procedures and were then presented with the informed consent form. If the participant confirms their interest in continuing with study participation, they signed the consent form, followed by the measurements of some basic anthropometric variables, including age, gender, body height, body mass, foot length, ankle width, knee width, ankle height, and inter-ASIS distance. Then, participants stepped on a regular treadmill without shoes for a 3-min warmup.

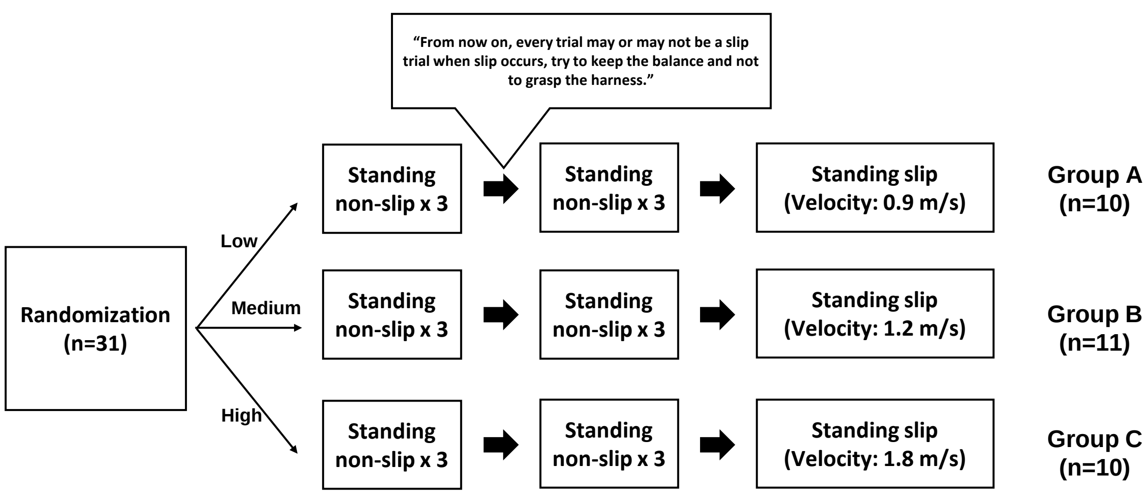

Fig. 2. Schematic of the study design for testing the effects of perturbation intensity on slip outcome in healthy young adults. Thirty-one subjects were randomly assigned into three groups: low (the peak belt speed = 0.9 m/s), medium (1.2 m/s), and high intensity (1.8 m/s) groups. After the warmup session and six standing trials on the treadmill, participants were exposed to an unexpected standing-slip with the assigned intensity.

Following a 3-min break, twenty-six reflective markers were attached to participants' bony landmarks using double-sided tape. One additional reflective marker was placed on the treadmill belt to record its movement, and two more markers were attached to the treadmill frame. Participants donned a safety harness and stepped on the ActiveStep treadmill (Simbex, NH, Fig. 3.). The harness was attached to an overhead arch from the shoulders via ropes. The ropes' length was adjusted so that no body parts except the feet were in contact with the belt surface if a fall occurred without affecting the participants' movements. The feet position at the beginning of each trial was clearly marked by tapes on the frame of the treadmill.

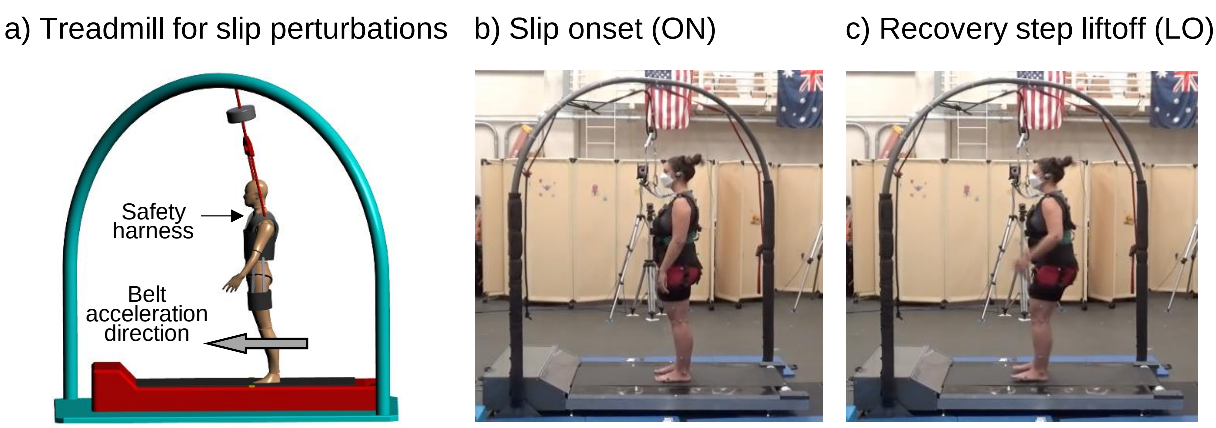

Fig. 3. Schematic of the a) ActiveStep treadmill used to induce the standing-slip perturbation for all three groups. Participants were protected by a full-body safety harness while on the treadmill. Pictures of (b) the slip onset and (c) the recovery step liftoff on the treadmill.

Participants were informed that for the first three trials, they were performing normal standing (10-sec each). Before recording each trial, subjects were instructed that "stand upright and look forward." Following these three trials, participants were told that for the remaining standing trials, they may or may not experience a "slip-like" movement on the treadmill without knowing when and how it occurred. They were also informed that "if a slip occurs, please try your best to keep the balance and not to grasp the harness." The first three standing trials with a slip possibility did not actually involve a slip. Next, the novel and unexpected standing slip happened.

The standing slip was induced by quickly accelerating the treadmill belt forward during quiet standing from stationary to the assigned speed within a certain time window and then decelerating the belt speed to zero over the same duration. The peak belt velocity was 0.9, 1.2, and 1.8 m/s for groups A, B, and C, respectively (Fig. 4.b). The duration and acceleration level were 0.8 s and 2.25 m/s^2 for group A, 0.6 s and 4 m/s^2 for group B, and 0.4 s and 9 m/s^2 for group C (Fig. 4.). Although the peak belt speed and slip duration differed between groups, the belt slip distance was identical as 0.36 m in all groups (Fig. 4.c).

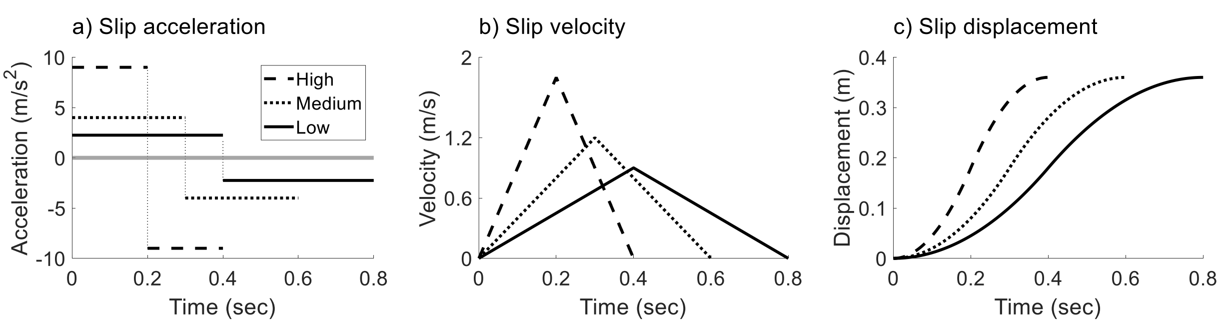

Fig. 4. The profile of the slip perturbation induced by the treadmill with the (a) slip acceleration, (b) slip velocity, and (c) slip displacement for each intensity group.

Full-body kinematic data were collected by 9-motion capture cameras (Vicon Motion System, UK) through the 26 cerebral hemisphere reflective markers on the bony landmarks. The extra three markers were attached to the treadmill to calculate the belt displacement after slips and to the treadmill floor to determine the liftoff (LO) of the recovery step following a slip.

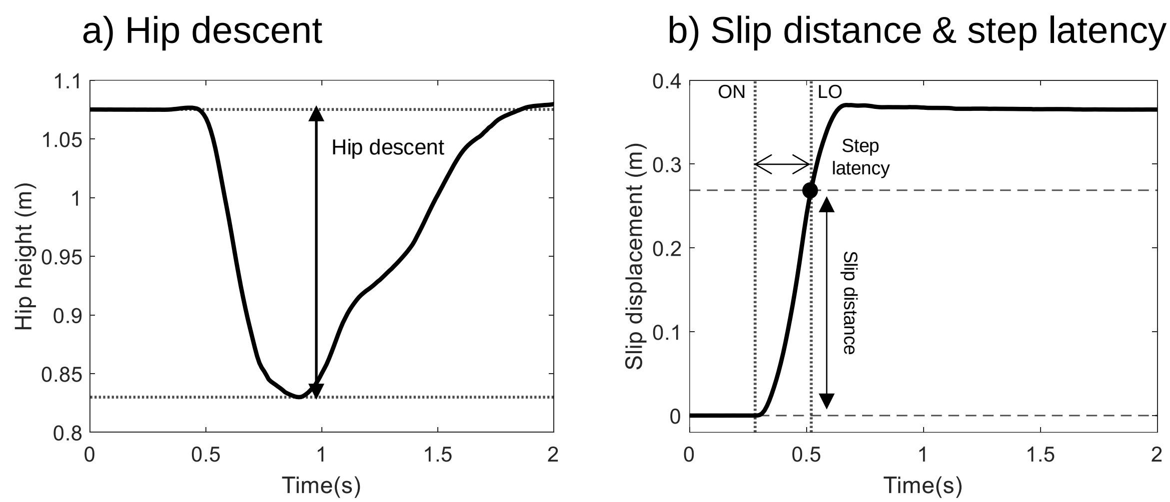

Fig.5. The graphic explanation of a) hip descent and b) slip distance and step latency during the slip perturbation. The black circle in b) indicated the liftoff instant.

Data Reduction

The standing slip trial was analyzed. Marker paths were low-pass filtered using fourth-order, zero-lag Butterworth filters at cut-off frequencies (ranging from 4.5 to 9 Hz) (Winter, 2005). Joint center, heel, and toe locations were computed from the filtered marker positions (Vaughan et al., 1992). For the standing-slip, slip onset (ON) was identified as the instant when the anteroposterior position of the belt marker is three standard deviations above baseline. The first recovery step for this slip trial was the initial backward step taken after ON. The standing-slip step event (LO) was identified from the foot kinematics with respect to the treadmill floor indicated by the two extra markers on the treadmill frame. Video recordings verified the LO event.

The body COM kinematics was computed using gender-dependent segmental inertial parameters based on the joint centers' locations (De Leva, 1996). The slip outcome was a binary variable: fall or recovery. Each slip trial was visually inspected to determine if a fall had occurred. A slip trial was considered a fall if the participant lost the balance and was clearly supported by the harness and the ropes connected to the harness were fully stretched. If there was any ambiguity, the relevant trial would have been further reviewed by additional researchers for an independent decision. If a slip was not deemed a fall, it was classified as a recovery trial (Yang and Pai, 2011). The primary outcome measure of the faller rate was calculated for each group as the percentage of the number of fallers to the number of the total subjects in the respective group.

The two components of the COM motion state (i.e., its position and velocity) were calculated relative to the rear of the base of support (BOS) and normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, respectively, where g is the gravitational acceleration and bh denotes the body height. The dynamic stability was calculated using FSR theory at ON and LO. Based on the FSR theory, the shortest distance from the COM motion state to the FSR's threshold against backward balance loss is the value of dynamic stability, one secondary outcome measure. Dynamic stability was calculated at ON and LO.

Other secondary outcome variables included the slip distance, recovery step latency, and hip descent. Slip distance was the belt displacement from its baseline position to the one at LO. Slip distance was normalized by the *bh*. Step latency was defined as the time duration between ON and LO. The hip descent was also determined as the vertical displacement of the mid-hip point from its baseline value to the lowest position after the ON. The hip descent was also normalized to the *bh*.

Statistical Analysis

Normality and homogeneity of variance were checked prior to analyses for all variables with Shapiro-Wilk and Levene's tests, respectively. Variables that are not normally distributed were transformed as needed depending on the skew direction. For variables that continue to violate the normality assumption following transformation, the non-parametric Mann-Whitney *U* test was used for statistical analysis.

To test the first hypothesis, the χ^2 test was conducted to compare the slip outcome (fall or recovery) between groups. If a significant difference was observed, pairwise χ^2 testes with Bonferroni correction followed to identify the source of the difference. The secondary (dynamic stability, recovery step latency, hip descent, and slip distance) outcome variables were analyzed by using the one-way analysis of variance (ANOVA) among groups (A vs. B vs. C) to verify the second hypothesis. If there is any significant effect associated with the group, independent *t*-tests with Bonferroni corrections were conducted as post-hoc tests. All statistical analyses were conducted using SPSS 27.0 (IBM, NY) with an alpha level of 0.05.

Results

Incidence of Recovery Step

After the unexpected slip, all participants in groups A and B and half of the participants in group C took a backward recovery step attempting to recover the balance. The remaining five participants in group C did not take a recovery step before they fell after the slip.

Faller Rate & Hip Descent

Our results showed that participants in the high-intensity group fell significantly more than the other two groups responding to the slip ($p < 0.001$, Fig. 6.a). Post-hoc pairwise χ^2 testes with Bonferroni correction exhibited that the fall rate was significantly higher in group C compared to A and B ($p < 0.001$ for group A, and $p = 0.002$ for group B, Fig. 6.a). The faller rate of group B was also significantly higher than the rate of group A ($p = 0.034$, Fig. 6.a). The hip descent displayed a significant difference between groups ($p < 0.001$, Fig. 6.b). Post-hoc independent *t*-tests indicated that the hip descent was significantly greater in group C than in groups A and B ($p < 0.001$ for both, Fig. 6.b). However, the hip descent of group B was not significantly different compared to group A ($p = 0.328$, Fig. 6.b).

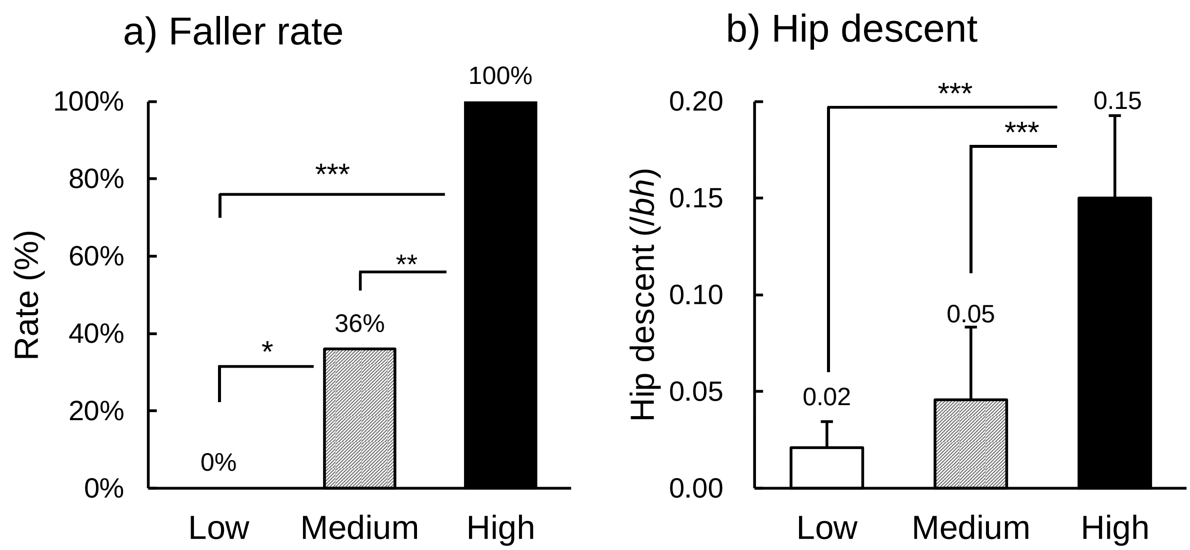

Fig. 6. Comparisons of a) the faller rate (%) and b) hip descent (normalized by *bh*, unitless) between three groups experiencing different slip intensities (A = low, B = medium, and C = high). The faller rate was calculated as the ratio of the number of fallers to the number of participants in the corresponding group. The hip descent was determined as the vertical displacement of the mid-hip point between the baseline position and the lowest point after the slip. It is normalized to body height (*bh*). (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$)

Dynamic Stability

The position of COM and dynamic stability did not exhibit significant differences among groups at ON ($p = 0.413$ for Fig. 7.a, and $p = 0.301$ for Fig. 7.e). The velocity of COM was significantly different among groups at ON ($p < 0.001$, Fig. 7.c). Post-hoc *t*-test denoted that the COM velocity in group C was significantly faster than other groups at ON ($p < 0.001$ for both, Fig. 7.c).

At the event of LO, there were significant differences among groups in the relative position and velocity of COM to the BOS ($p < 0.001$, Fig. 7.b and $p = 0.012$, Fig. 7.d) and dynamic stability

($p < 0.001$, Fig. 7.f). Post-hoc independent *t*-test indicated that the COM was located more posteriorly relative to the BOS in group C than the other two groups ($p < 0.001$ for both, Fig. 7.b). The COM moved backward faster in group C than in group A ($p = 0.01$, Fig. 7.d) but not in group B ($p = 0.585$, Fig. 7.d). Combining the position and velocity of COM, dynamic stability in group C was more unstable than in groups A and B ($p < 0.001$ for both, Fig. 7.f).

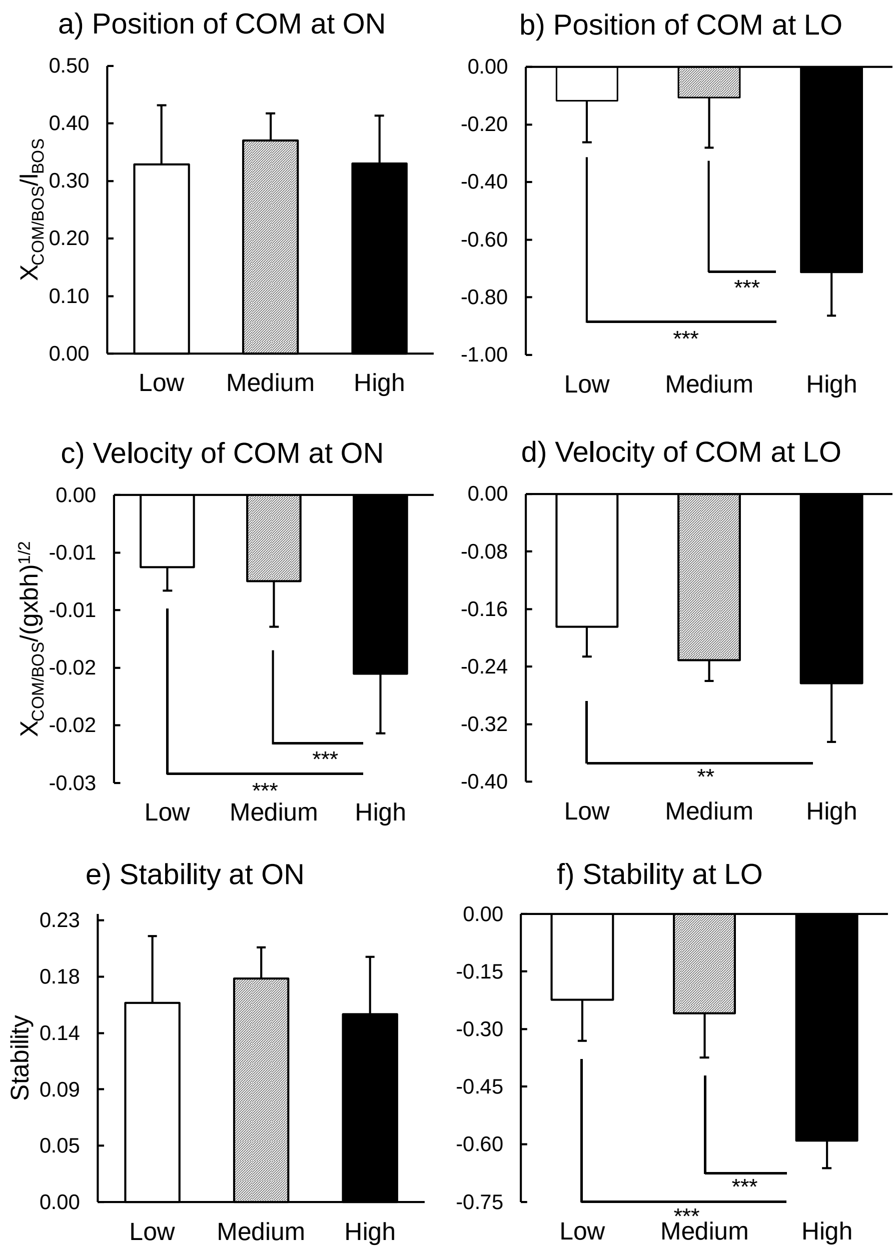

Fig. 7. Comparisons of (a) the position of the center of mass (COM) at the slip onset (ON), (b) the position of the center of mass (COM) at liftoff (LO), (c) the velocity of the COM at ON and (d) the velocity of the COM at LO, (e) dynamic stability at ON and (f) dynamic stability at LO in response to the unexpected standing slip among three groups. The COM position is relative to the rear edge of the base of support (BOS) and respectively normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, where *g* represents the gravitational acceleration and *bh* is the body height. Dynamic

stability is calculated as the shortest distance from the given COM motion state to the threshold against backward balance loss. (**: $p < 0.01$, ***: $p < 0.001$)

Spatiotemporal Parameters

The spatiotemporal parameters were significantly different in the slip distance ($p < 0.001$, Fig. 8.a) and in the step latency ($p = 0.034$, Fig. 8.b). Post-hoc *t*-test denoted those individuals in group C slipped significantly more forward at LO than the other two groups ($p < 0.001$ for both, Fig. 8.a). The slip distance at LO did not show a significant difference between groups A and B ($p = 1.000$, Fig. 8.a). Post-hoc *t*-test indicated that participants in group B initiated the recovery step significantly sooner than their counterparts in group A ($p = 0.031$, Fig. 8.b). However, the step latency was not significantly different between groups A and C ($p = 0.486$), or B and C ($p = 1.000$, Fig. 8.b).

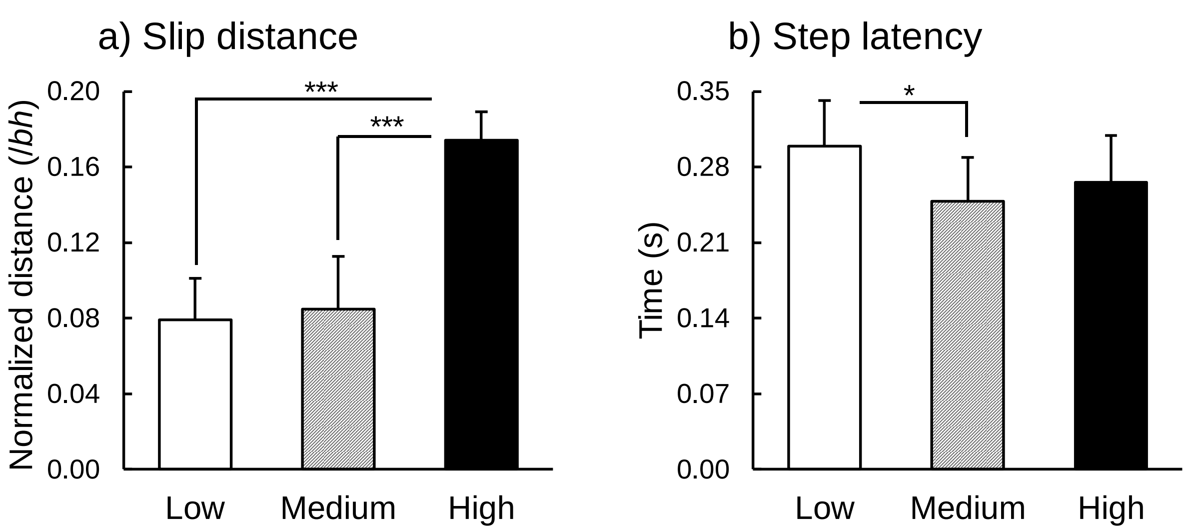

Fig. 8. Comparisons of (a) slip distance at the recovery LO and (b) latency of the recovery step in response to an unexpected standing-slip among three groups. The slip distance at liftoff is the displacement of the belt marker from the ON to LO. It is normalized to the body height (*bh*). The step latency is calculated as the time duration from ON to LO. (*: $p < 0.05$, ***: $p < 0.001$)

Discussion

The objective of this thesis project was to demonstrate how the slip perturbation intensity, as quantified by the peak slip velocity, alters the responses to an unexpected standing slip among young adults. The responses were characterized by slip-falls, hip descent, dynamic stability, slip distance at recovery liftoff, and the recovery step latency. The main findings of this study were:

(1) The increased slip intensity raises the risk of falling after a standing-slip in healthy young adults.

(2) A high slip intensity impairs dynamic stability by mainly placing the COM more posteriorly relative to the BOS than a low intensities.

(3) The higher the slip intensity, the larger the hip descent and the longer the slip distance at LO a young adult would encournter during a standing slip.

The findings of this study fully supported the first hypothesis that a high slip intensity would lead to a greater fall rate than a low slip intensity during standing. Specifically, all participants in the high-intensity group fell; four out of 11 in the medium group experienced a fall; and none of the participants in the low-intensity group fell (Fig. 6). This study, for the first time, quantified how the slip intensity affects slip outcome among at least young adults. The findings could provide guidance when designing a slip-based training protocol. A slip profile that is more conservative than the low-intensity group may not induce falls, which may not be sufficient to allow the participants to develop the necessary skills for preventing falls. On the other hand, a slip profile that is similar to or more aggressive than the high-intensity group could be excessively severe as some participants may not be able to initiate the recovery step. For example, five participants in the high-intensity group did not take a recovery step. The untaken recovery step could compromise the effects of perturbation-based training. Specifically, an effective and successful recovery step is the key to restoring balance and avoiding falls after a perturbation (Pai et al., 2014; Simpkins and Yang, 2023; Yang et al., 2019) given that a fall could materialize within a fraction of a second (Qiao and Yang, 2020). It is important to allow participants to experience taking recovery steps after the perturbation. This would ensure the effects of the slip-based perturbation training on reducing falls. Therefore, the low and high intensities examined in this study could define the ideal range of the intensity level for designing a slip-based training profile.

The results partially supported the second hypothesis that the responses to the slip perturbation would be less effective in the higher intensity groups than in the lower intensity groups following the unexpected standing slip in young adults. Specifically, the results indicated that individuals in the high-intensity group were significantly more unstable at LO than those in the other two groups, while the difference in stability at LO was not significant between the low and medium intensity groups. The slip distance at LO was significantly longer for the high-intensity group than for the other two groups. However, the slip distance between the low and medium intensity groups was comparable. The only significant difference in the recovery step latency was between the low and medium groups.

The worst dynamic stability at LO for the high-intensity group (or group C) could be due to their significantly longer slip distance than the other two groups. The longer slip distance in group C may be attributed to the fastest belt velocity of the slip profile. Given that the step latency was not different between group C and groups A or B (Fig. 8.b), the fastest belt speed in group C moved the feet or the BOS more anteriorly in group C than in the other two groups. The longer slip distance would place the BOS more forward in group C than in groups A and B. Consequently, the COM was more posteriorly relative to the BOS at LO in group C than in the other two groups. Additionally, the BOS was moving at a faster speed in group C than in the other two groups at LO again due to the highest belt speed (Fig. 4.b). Therefore, the relative COM velocity to the BOS was slower in group C compared to the other two groups. Based on the FSR framework, the relative COM position and velocity to the BOS are the two critical components determining dynamic stability (Espy et al., 2010a; Yang et al., 2007). A more posteriorly placed and slowly moving COM with respect to the BOS would lead individuals in group C to be more unstable against backward balance loss than the other two groups. This could account for the worst dynamic stability at LO for the high intensity group than the other two groups. As dynamic stability is a precursor of backward falling after a slip, this also explains the higher faller rate in this group than their lower intensity counterparts.

The comparable stability at LO between the two lower intensity groups could also be explained by the similar slip distance and COM velocity at this event. The alike slip distance between these two groups is the outcome of the slip profile and the step latency. Specifically, the step latency was longer in the low-intensity group (or group A) than in the medium group (or group B). However, the belt speed moved more slowly in the former group than in the latter one. As the slip distance is the product of the belt speed and the duration (or the step latency in the present study), the slip distance at LO was similar between these two lower intensity groups. At LO, the COM velocity relative to the BOS was similar between these two groups (-0.18 ± 0.04 vs. -0.23 ± 0.03). According to the FSR concept, dynamic stability against backward falling was comparable between these groups due to the similar COM motion state between these two groups. This seems to contradict the finding related to the slip-fall outcome as more individuals in group B fell more than in group A. This could be tied to the fact that dynamic stability only governs the COM-BOS kinematic relationship in the horizontal direction, but a fall ultimately is the collapse of the body in the vertical direction (Yang et al., 2011). In the present study, individuals in group B exhibited a significantly larger hip descent than in group A (Fig. 6.b). Hip descent has been used as an indicator of limb support (Yang et al., 2009). This implies that group B individuals were unable to provide sufficient limb support after taking the recovery step compared to those in group A. Insufficient limb support could lead to a vertical limb collapse and thus a fall.

Interestingly, the step latency in the medium group was shorter than the one in the low-intensity group, while the high-intensity group's step latency was not different from the other groups. Previous studies which applied a same slip intensity perturbation to both the experimental and control groups reported that a longer slip distance is associated with a longer step latency (Peterson and Horak, 2016; Simpkins et al., 2022). One recent study investigating the stepping response under three different slip profiles suggested that the higher slip intensity could lead to shorter step latency in healthy young adults (Jeon et al., 2022). Our results partially concurred with the findings of the previous study. In detail, the belt speed profile was presented as a "triangle wave" in this present study while the previous study adopted a "square" wave (Jeon et al., 2022). For a triangle-wave slip profile, the belt speed would accelerate first followed by its deceleration in the second half of the profile (Fig. 4.b). However, the belt speed would almost remain constant during the entire profile for the square-wave slip profile. The dissimilar slip profile and intensity could impose different disruptions on the human body. Despite the dissimilarity of slip profiles, the high-intensity slip perturbation would cause a shorter step latency than a low-intensity slip in healthy young adults. Therefore, more studies are needed to further examine how step latency is affected by the slip profile and its intensity.

It should be noted that five participants in the high-intensity group did not take a recovery step before they were fully caught by the harness. One possible reason might be that the perturbation was too fast for the participants in group C to react promptly by initiating the recovery step. To take a recovery step, the body's central nervous system needs to collect the afferent input, process the information, and make the efferent motor commands to engage the relevant muscles in order to respond to the perturbation (Nielsen and Sinkjaer, 2002). It is possible that the slip perturbation occurred excessively fast and does not allow those five individuals in group C to initiate the recovery step. Further studies which monitor the leg muscle electromyography activities after a slip are needed to test this postulation.

In conclusion, as the first attempt to compare the effects of the slip intensity on body reactions and slip outcome during an unexpected standing slip, the current study indicated that the slip intensity significantly affects the slip outcome and participants' reactions to the perturbation among young adults. This information could be used to establish the guidelines for choosing intensity as a training protocol or assessment platform for rehabilitation and fall prevention involving slip-like perturbations.

Further Directions

There are several possible directions for future studies. First, potential studies should consider more perturbation intensity profiles. The current study only used three of many possible slip profiles (high, medium, and low). Second, the peak belt velocity was used as the index of the slip intensity. Although this is useful, it is only one of the three metrics associated with a slip profile. It could also be meaningful to use the belt acceleration as the measurement of the slip intensity. Additionally, it is necessary to examine how these three parameters intercorrelate with each other to shape the intensities and the disturbance to the body balance. Third, it remains unknown how our findings can be generalized to other populations under different types of perturbations, such as trips. Future work investigating the effects of slip intensity on the slip outcome among older adults or individuals with medical conditions is needed to expand the understanding for our findings' generalizability. Lastly, only one slip was investigated in this study. It stays unclear how young adults could adapt to repeated slips with various intensities. Given that perturbation-based training is increasingly used as a training paradigm to reduce falls in various populations, it would be of interest to study how the human body adapts to repeated slips under different intensity levels. Studies with rigorous design and large sample sizes are desired to address these questions.

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