Non-Treadmill Trip Training – Laboratory Efficacy, Validation of Inertial Measurement Units, and Tripping Kinematics in the Real World

Youngjae Lee

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
In
Industrial and Systems Engineering

Michael L. Madigan, Chair
Julia Castleberry
Sunwook Kim
Sol Lim
Maury A. Nussbaum

April 30, 2024
Blacksburg, Virginia

Keywords: trip-induced falls, older adults, reactive balance, perturbation-based balance training, wearable sensors, loss of balance, biomechanics

Non-Treadmill Trip Training – Laboratory Efficacy, Validation of Inertial Measurement Units, and Tripping Kinematics in the Real World

Youngjae Lee

ABSTRACT

Trip-induced falls are a leading cause of injuries among adults aged 65 years or older. Perturbation-based balance training (PBT) has emerged as an exercise-based fall prevention intervention and shown efficacy in reducing the risk of trip-induced falls. The broad goal of my PhD research was to advance the application of this so-called trip training through three studies designed to address existing knowledge gaps. First, trip training is commonly conducted with the aid of costly specialized treadmills to induce trip-like perturbations. An alternative version of trip training that eliminates the need for a treadmill would enhance training feasibility and enable wider adoption. The goal of the first study was to compare the effects of non-treadmill training (NT), treadmill training (TT), and a control (i.e., no training) on reactive balance after laboratory-induced trips among community-dwelling older adults. After three weeks of the assigned intervention, participants were exposed to two laboratory-induced trips while walking. Results showed different beneficial effects of NT and TT. For example, NT may be more beneficial in improving recovery step kinematics, while TT may be more beneficial in improving trunk kinematics, compared to the control. While the first study showed the effects of PBT on laboratory-induced trips, little is known about how such training affects responses to real-world trips. Responses to real-world trips may be captured using wearable inertial measurement units (IMUs), yet IMUs have not been adequately validated for this use. Therefore, the goal of the second study was to investigate the concurrent validity of IMU-based trunk kinematics against the gold standard optical motion capture (OMC)-based trunk kinematics after overground trips among community-dwelling older adults. During two laboratory-induced trips, participants wore two IMUs placed on the sternum and shoulder, and OMC markers placed at anatomical landmarks of the trunk segment. Results showed that IMU-based trunk kinematics differed between falls and recoveries after overground trips, and exhibited at least good correlation (Pearson's correlation coefficient, $r > 0.5$) with the gold standard OMC-based trunk kinematics. The goal of the third study was then to explore differences in tripping kinematics between the laboratory and real world using wearable IMUs among community-dwelling older adults. Participants were asked to wear three IMUs (for sternum and both feet) and a voice recorder to capture their responses to real-world losses of balance (LOBs) during their daily activities for three weeks. Results showed a higher variance in laboratory-induced trips than real-world trips, and the study demonstrated the feasibility of using IMUs and a voice recorder to understand the underlying mechanisms and context of real-world LOBs. Overall, this work was innovative by evaluating a non-treadmill version of trip training, establishing the validity of IMUs in capturing kinematic responses after overground trips, and applying IMUs and a voice recorder to assess tripping kinematics in the real world. The results from this work will advance the use of PBT to reduce the prevalence of trip-induced falls and to investigate the real-world effects of such trip training in future studies.

Non-Treadmill Trip Training – Laboratory Efficacy, Validation of Inertial Measurement Units, and Tripping Kinematics in the Real World

Youngjae Lee

GENERAL AUDIENCE ABSTRACT

Trips and falls are a major health problem especially among older adults who are aged 65 years or older. Researchers have developed an innovative exercise-based fall prevention training program, which has shown to be helpful in reducing trips and falls. The broad goal of my PhD research was to advance the use of this so-called trip training through three new research studies. First, specialized treadmills are commonly used for trip training to simulate trip-induced falls. An alternative version of trip training without a treadmill would allow more people to receive benefits from this training. The goal of the first study was to compare the effects of non-treadmill training (NT), treadmill training (TT), and no training on balance recovery after tripping in the laboratory. Older adults living in the local community were recruited as research participants and completed NT, TT, or no training over three weeks. After that, they attended a laboratory session where they were tripped twice while walking on a walkway. Results showed that NT helped to take a longer and faster recovery step, while TT helped to limit trunk forward bending during tripping, both of which are important movements to prevent falling after tripping. While the first study showed benefits of trip training in the laboratory, not much is known about the benefits of trip training in the real world. Wearable sensors called inertial measurement units can record body movements without laboratory motion capture cameras, but their ability to record dynamic body movements during tripping needs to be tested. The goal of the second study was to evaluate the capabilities of these wearable sensors on recording trunk movements during tripping and compare them to those recorded by laboratory motion capture cameras. Participants were tripped twice in the laboratory, and their trunk movements were recorded by several wearable sensors and laboratory motion capture cameras. Results showed that these wearable sensors can distinguish between fallers and non-fallers after tripping, and that the trunk movements recorded by the wearable sensors were associated with those recorded by the laboratory motion capture cameras. With this confirmation, the third study was designed to compare balance recovery after tripping between the laboratory and real world using wearable sensors. Participants were asked to wear three wearable sensors and a voice recorder during their daily activities for three weeks. The wearable sensors recorded their trunk and feet movements, while the voice recorder was used for participants to provide detailed explanations of balance losses they experienced. Results showed a higher variability in balance recovery from the laboratory trips compared to the real-world trips. In addition, this study demonstrated that wearable sensors and a voice recorder can be used to study how people reacted to a balance loss and what they did to recover (or fall) from it. Overall, my PhD research work suggested a new version of trip training that does not require a treadmill, proved that wearable sensors can be used to record important body movements during tripping, and demonstrated the method to study balance recovery responses in the real world using wearable sensors. The results from the three studies will promote the use of trip training and provide guidelines for evaluating benefits of trip training in the real world.

Acknowledgements

When I first attended Virginia Tech as a first-year undergraduate student many years ago, I never thought that I would have such a long academic journey and eventually earn a doctoral degree. I could not have achieved this huge accomplishment without support from many people. Below I would like to acknowledge some of the special people to express my sincere gratitude.

Dr. Michael L. Madigan – I cannot express enough how grateful I am to have someone like you as my advisor and mentor throughout the years of being a graduate student. Especially, your encouragement and guidance when I was in doubt about my ability to do things helped me a lot to break the boundaries of my comfort zone and challenge myself for another meaningful accomplishment.

My advisory committee Drs. Julia Castleberry, Sunwook Kim, Sol Lim, and Maury A. Nussbaum – Thank you for your invaluable feedback on my PhD research. I also really appreciate your support and encouragement in filling out many job applications.

Dr. Divya Srinivasan – Although our journey ended earlier than I anticipated, I would like to express my gratitude to you for introducing me to the field of physical ergonomics and biomechanics research, and for letting me work with you while you were at Virginia Tech.

Occupational Ergonomics and Biomechanics Laboratories members – I enjoyed getting to know all of you and working with some of you on several research projects. I wish you the best of luck in your remaining MS/PhD years. Special thanks to Gabby, Reza, Michelle, Asa, and many other graduate/undergraduate research assistants who were the members of Madigan Biomechanics Group while I studied at Virginia Tech. Your contribution in data collection/analysis was tremendous help for me.

Family and friends – Thank you for being there for me always when I needed support and encouragement. You are the reason why I was able to endure some of the toughest times during my long academic journey.

Lastly, research participants – I sincerely thank you again for your participation in my research studies.

Table of Contents

Specific Aims

Trip-induced falls remain highly prevalent and a major source of injuries despite mitigation efforts. Research has shown that many trip-induced falls result from an ineffective kinematic response to a trip-induced loss of balance (LOB). Perturbation-based balance training (PBT) is an innovative approach to fall prevention that leverages motor learning principles through repeated exposure to perturbations that induce a LOB in a safe, controlled manner to improve the effectiveness of these responses. So-called trip training is a task-specific version of PBT using simulated trips as perturbations to target trip-induced falls. Trip training studies have demonstrated efficacy through improved fall rates and kinematic responses after laboratory-induced trips.

The broad goal of my PhD dissertation research was to advance the application of trip training for fall prevention by addressing three knowledge gaps. First, trip training is commonly conducted with the aid of costly specialized treadmills (i.e., treadmill training or TT). An alternative non-treadmill training (NT) regimen that does not require a specialized treadmill would enhance its feasibility and enable wider adoption. Second, kinematic responses to real-world LOBs may be captured using wearable inertial measurement units (IMUs), yet the validity of their use for this application needs to be evaluated. Third, trip training has been shown to reduce fall rates and improve reactive balance after laboratory-induced trips, but the translation of these effects to the real world remains unclear. Wearable IMUs enable real-world kinematic assessment and may allow comparison in tripping kinematics between the laboratory and real world. Below three studies are proposed:

Specific Aim #1: Compare the effects of NT, TT, and a control on reactive balance after laboratory-induced trips. Thirty community-dwelling older adults (age 65-80) were assigned to either NT (n=10), TT (n=10), or a control (n=10). Participants attended six training sessions in the laboratory over three weeks and then completed a post-training experimental session involving two laboratory-induced trips. Outcome measures were key kinematic measures associated with successful balance recovery after laboratory-induced trips.
<u>Hypothesis 1</u>: NT and TT participants will exhibit improved fall rates and reactive balance compared to control participants.
<u>Hypothesis 2</u>: TT participants will exhibit a lower fall rate and better reactive balance compared to NT participants.

Specific Aim #2: Investigate the concurrent validity of IMU-based trunk kinematics against optical motion capture (OMC)-based trunk kinematics after laboratory-induced trips. All 30 participants from Aim 1 wore both IMUs and OMC markers to capture their trunk kinematic responses after laboratory-induced trips. The concurrent validity of key trunk kinematic measures of trip recovery from IMUs was determined by comparison with the same measures from a gold-standard OMC system.
<u>Hypothesis 3</u>: Change in trunk angle and sternum drop measured by both IMUs and OMC will differ between falls and recoveries, and exhibit at least good correlation (Pearson's correlation coefficient, $r > 0.5$) between the two systems.
<u>Hypothesis 4</u>: Change in trunk angle and sternum drop measured by a participant-placed sternum IMU will exhibit a larger variance in their errors against OMC (i.e., difference between IMUs and OMC) than a researcher-placed sternum IMU.

Specific Aim #3: Explore differences in tripping kinematics between the laboratory and real world – A Pilot Study. Twenty participants from Aim 1 (TT and control participants) were asked to wear IMUs during their daily life for three weeks to capture their kinematic responses to real-world trips. After that, they were exposed to two laboratory-induced trips. Outcome measures were key trunk kinematic measures of trip recovery.
<u>Hypothesis 5</u>: Tripping kinematics will exhibit a higher variance in the real world than in the laboratory.

This work is innovative by evaluating a non-treadmill version of trip training that requires lower cost and less equipment, establishing the validity of IMUs in capturing kinematic responses after overground trips, and applying IMUs to assess tripping kinematics in the real world. The results from this work will advance the use of PBT, and hopefully enable its wider use to reduce the prevalence of trip-induced falls.

Chapter 1. Background

1.1. Slips, Trips, and Falls

Slips, trips, and falls (STFs) among older adults are highly prevalent and a significant cause of morbidity and mortality (Bergen et al., 2016; Houry et al., 2016; Stevens et al., 2014). According to Centers for Disease Control and Prevention (2017), unintentional falls are the leading cause of non-fatal and fatal injuries among individuals aged 65 years or older in the United States. A survey conducted in 2014 reported that 29% of older adults fell at least once in the last 12 months for a total of 29 million falls, of which seven million resulted in injuries (Bergen et al., 2016). In 2015, the medical expenditure attributable to fatal and non-fatal injurious falls among older adults was approximately $50 billion (Florence et al., 2018). With the current growth of the older population, STF prevalence, their associated injuries, and their associated medical costs are also expected to increase (Cigolle et al., 2015; Houry et al., 2016; Murray et al., 2012).

Slips are a common cause of falls. Slips are responsible for about 40% of all outdoor falls among community-dwelling older adults (Luukinen et al., 2000). Such slips may lead to sprains/strains (Yoon & Lockhart, 2006) and fractures (Yang et al., 2012). Slips occur when the friction needed to prevent excessive relative movement at the interface between the walking surface and the shoe sole (i.e., required friction) exceeds available friction at this interface (Redfern et al., 2001). Slips typically occur at heel-strike or toe-off of the gait cycle (Redfern et al., 2001). Slips at heel-strike are generally considered more difficult to recover from and therefore are more likely to lead to a fall (Redfern et al., 2001). For this reason, this chapter will focus on slips at heel-strike. Slips at heel-strike typically result in backward loss of balance (LOB). Slip severity is commonly determined using slip distance and peak slip velocity (Redfern et al., 2001), with one study suggesting that a slip will likely result in a fall if the slip distance exceeds 10 cm or if the peak slip velocity exceeds 0.5 m/s (Strandberg, 1983).

Appropriate reactive balance responses of the slipping and trailing (non-slipping) feet may arrest slips and help avert a fall. For instance, hip extension and knee flexion of the slipping limb may decelerate the slipping foot (Cham & Redfern, 2001). Lowering of the trailing limb, which is supposed to begin swing phase if it was normal walking, and the extension of its knee and hip can also provide more stability by increasing the base of support (Marigold et al., 2003). In addition, Allin et al. (2018) suggested that quickly arresting the motion of the slipping foot and placing the trailing toe approximately 0-10% body height anterior to the sacrum may help avoid a slip-induced fall.

Trips are also a common cause of falls. Trips contribute to 29-53% of falls among community-dwelling older adults (Berg et al., 1997; Blake et al., 1988; Stevens et al., 2014). Such trips may lead to various injuries, such as sprains/strains, contusions, lacerations, and fractures (Lipscomb et al., 2006; Troy & Grabiner, 2007). Trips occur during swing phase of the gait cycle when the forward motion of the swing foot is obstructed due to inadequate clearance with an obstacle (Chang et al., 2016; Grabiner et al., 1993). Trip-induced falls typically result in forward LOB. Minimum foot (or toe) clearance is the smallest vertical distance between the ground and the swing foot (or toe) near mid-swing phase, during which one is particularly vulnerable to trips (Winter, 1992). A decrease in minimum foot clearance or increase in foot clearance variability are both independently associated with an increased risk of tripping (Begg et al., 2007).

Studies have investigated the requisites for successful balance recovery after a trip. Reactive stepping characteristics, and trunk kinematics at the completion of the initial recovery step, are considered important to avert a trip-induced fall (Owings et al., 2001; Van Dieen et al., 2005). More specifically, quickly arresting trunk flexion (i.e., smaller trunk flexion angle and velocity), completing a recovery step to sufficiently extend the base of support, and maintaining sufficient hip height are significant to prevent falling after a trip (Grabiner et al., 2012; Pavol et al., 2001; Pijnappels et al., 2005).

1.2. Fall Prevention Interventions

Numerous fall prevention interventions are available including non-exercise and exercise-based interventions. In general, these interventions attempt to address risk factors for falls (Table 1.1). Non-exercise fall prevention interventions target individual, environmental, and behavioral risk factors. Examples include medical evaluation/intervention, e.g., low vision adaptations and medication review (Clemson et al., 2004; Davison et al., 2005; Harwood et al., 2005; Logan et al., 2010), environmental modification, e.g., identify and eliminate fall hazards at home (Campbell et al., 2005; Cumming et al., 1999; Kunzler et al., 2018; Logan et al., 2010), and behavioral education, e.g., improve home and community behavioral safety (Campbell et al., 2005; Clemson et al., 2004; Cumming et al., 1999; Logan et al., 2010). Exercise-based fall prevention interventions target individual and behavioral risk factors. Examples include strength (Buchner et al., 1997b; Claudino et al., 2021; Prata & Scheicher, 2015), balance (Gusi et al., 2012; Prata & Scheicher, 2015), endurance (Buchner et al., 1997a, 1997b), and flexibility training (Bird et al., 2009).

Table 1.1. Types of risk factors for falls and some examples.

Types	Examples
Individual	Muscle weakness, abnormalities in balance and gait, cognitive impairments, low vision, fear of falling
Environmental	Mats/rugs, footwear, lighting, stairs, electrical cords
Behavioral (or activity)	Awareness of hazards and falls, getting up from a chair

1.2.1. Exercise-Based Fall Prevention Interventions

Given that decreased strength is a risk factor for falling (Tinetti & Kumar, 2010), strength training is a common exercise-based fall prevention intervention. Different forms of strength exercise programs exist including resistance training (i.e., progressive and high-intensity exercises), which has shown 57.3% and 30.6% reduction in a fall risk score and sway after training, respectively, compared to other non-strength exercise programs, such as agility training and stretching, among community-dwelling older women aged 75-85 years old (Liu-Ambrose et al., 2004). However, a high heterogeneity in such strength exercise programs for fall prevention makes it difficult to draw definitive conclusions (Claudino et al., 2021). A recent systematic review and meta-analysis on strength training to prevent falls among older adults (Claudino et al., 2021) reported that strength training alone can be an effective exercise program as other unimodal or multimodal exercise programs for fall prevention in older adults. It suggested general strength training guidelines for reducing falls among older adults: (1) perform some form strength training three or more times per week, (2) progress intensity from low to moderate, and (3) include power-based strength training if possible. Further research is necessary to investigate the retention of such strength training effects and how often re-training is required.

Balance training is another exercise-based fall prevention intervention, given that balance impairment is another risk factor for falling (Granacher et al., 2011; Pfortmueller et al., 2014). Balance training can be categorized into steady-state and reactive balance exercises (Granacher et al., 2012). Steady-state balance exercises consist of tasks that challenge balance during voluntary static or dynamic motions, i.e., internal perturbations (Gerards et al., 2017; Mansfield et al., 2018). For example, static balance exercises can include unipedal and tandem standing (Sakamoto et al., 2006; Steadman et al., 2003), and dynamic balance exercises can include walking on the tips of the toes or on the heel and walking sideways (Madureira et al., 2007). On the other hand, reactive balance exercises utilize external perturbations while standing or walking to disturb one's balance. For example, reactive balance exercises apply postural disturbances by outside forces, like pushing and pulling by others or lean-and-release (Gerards et al., 2017; Mansfield et al., 2018). A systematic review and meta-analysis on exercises to prevent falls among older adults (Sherrington et al., 2017) showed that greater effects in reducing falls among older adults were found for exercise programs that challenge balance, which supports the importance of balance training as a fall prevention exercise. However, further research is needed to better understand dose-response relationships, retention of training effects, and re-training requirements for balance training, as well as to expand its adoption in wider range of population at high risk of falls (Lesinski et al., 2015).

A combination of strength and balance training has also been employed as an exercise-based fall prevention intervention to target these two major risk factors (Pfortmueller et al., 2014). For example, Otago Exercise Program is a home-based exercise program involving a series of lower extremity strengthening and balance (re)training exercises at increasing levels of difficulty, instructed by a physiotherapist who visits home during the first several months and remains in telephone contact afterward for advice as the participants continue the training at home by themselves. Campbell et al. (1999) reported women aged 80 years or older who participated in Otago for two years showed a significantly lower rate of falls than those who received usual care and social visits at home for the same two-year time frame (i.e., falls per person year = 0.83 and 1.19 for the Otago and control groups, respectively). A systematic review and meta-analysis (Thomas et al., 2010) reported that Otago lowered fall rates by 34% over 12 months after training first initiated and continued among community-dwelling older adults. Modified versions of Otago tailored to individual characteristics (e.g., health conditions and history of falls) and preferences (e.g., individual home-based vs. group and instructor-led vs. technology-based) were investigated (Martins et al., 2018). These modified versions improved physical function and balance, but it remains unclear whether they are as effective as the original program, and if these modified versions improve compliance given that greater effects can be achieved with higher compliance (Martins et al., 2018; Thomas et al., 2010).

Tai Chi is another exercise-based fall prevention intervention that has demonstrated wide use and effectiveness. It is a traditional Chinese mind-body exercise that is practiced for fitness and health, especially among older adults, because it is easy to learn and involves low-impact, slow-motion movements (e.g., weight shifting in different directions, awareness of body alignment, and coordination of arms, legs, and trunk) (Hu et al., 2016; Lan et al., 2013; Wang et al., 2004). Tai Chi has shown to reduce falls by 17-49% (Logghe et al., 2010), decrease in fear of falling, and improve balance (Hu et al., 2016; Leung et al., 2011; Logghe et al., 2010). A systematic review and meta-analysis (Hu et al., 2016) speculated that the combination of muscular, skeletal, and neural functions required during Tai Chi exercise may be the underlying mechanisms how Tai Chi helps reduce the risk of falls among older adults. Another systematic and meta-analytical review (Leung et al., 2011) stated that Tai Chi can improve postural stability, somatosensory awareness, and neuromuscular control. In addition, Leung et al. (2011) noted other benefits of Tai Chi including that it is easily understood and enjoyable by many older adults, requires no special equipment, and can be performed virtually anywhere and at any time. A few important questions remain, however, regarding the use of Tai Chi as an exercise-based fall prevention intervention. First, the optimal dosage of Tai Chi exercise for fall prevention remains unclear. Second, the retention duration of training benefits, or how often re-training is needed, are also unclear (Leung et al., 2011; Logghe et al., 2010).

1.2.2. Leveraging Motor Learning Principles

The exercise-based fall prevention interventions described above aim to address general aspects of physical function (e.g., strength and balance) based upon these factors being identified as risk factors for falls. The premise is that improving these general aspects of physical function will result in a reduction in fall risk. However, the transfer of such training improvements to the quick and specific LOB response needed to avert a fall may not be significant (Lurie et al., 2013; Mansfield et al., 2010; Pai et al., 2014). In fact, a review of fall prevention exercise interventions by Sherrington et al. (2017) concluded that exercises that challenge balance are most effective at fall prevention. Another exercise-based fall prevention approach is to leverage principles of motor learning. According to motor learning theory, the movements and sensory stimuli used during training should closely match the movements and sensory stimuli used during the task of interest for permanent change in behavior (i.e., specificity of training) (Bachman, 1961; Gliner, 1985;

Hubbard et al., 2009). Because many falls occur as a result of a deficient kinematic response to a LOB, a motor learned-based training regimen that aims to improve the kinematic response to a LOB may be a viable approach for reducing falls (Grabiner et al., 2012; Grabiner et al., 2014; Granacher et al., 2011; Takacs et al., 2013).

Perturbation-based balance training (PBT) has emerged to incorporate the principles of motor learning to an exercise-based fall prevention intervention (Gerards et al., 2017). Volitional step training regimens are one type of PBT designed based upon the premise that preventing falls after a LOB commonly requires stepping to expand the body's base of support (Owings et al., 2001). During volitional step training, participants are instructed to voluntarily step on targets (e.g., step pads, mats, or marks on the floor) or over obstacles upon a cue to practice stepping under various conditions using different speeds, directions, and step lengths (Okubo et al., 2017; Schoene et al., 2013; Shigematsu & Okura, 2006). For example, Shigematsu and Okura (2006) developed a square stepping exercise program that involves participants stepping on squares on a mat in a specified order that varies difficulty level. They reported that older adults aged 60-80 years who completed the program showed improvements in agility, leg power, locomotion speed, flexibility, and balance, all of which constitutes a risk factor for falls if lacking. In addition, Schoene et al. (2013) asked adults aged 65 years or older to complete an exergame (i.e., a computerized step pad system connected to TV) to practice stepping, with instructions presenting different directions and timings of steps through the screen. They showed that participants who completed the exergame over eight weeks improved physical and cognitive parameters of fall risks (i.e., step reaction and movement times, postural sway, and contrast sensitivity). While these studies have demonstrated clear benefits with respect to fall prevention, volitional step training may not mimic the need to quickly respond to an unexpected LOB that commonly occurs in real life (Luchies et al., 1999; Mansfield et al., 2010; Pai et al., 2014).

Another type of PBT that uses larger, more sudden perturbations than volitional step training is reactive balance training. It differs from volitional step training by applying some form of unexpected postural perturbation to participants. Studies have used a variety of strategies to apply perturbations including specialized treadmill or moveable platform to induce perturbations while participants were standing, and ground surface compliance changes or treadmill belt accelerations/decelerations while participants were walking (Aviles et al., 2019; Grabiner et al., 2012; McCrum et al., 2017). Based upon motor learning theory, repeated exposure to perturbations, along with associated sensory feedback on performance, can elicit improvements in the neuromuscular responses to these perturbations and resulting LOB. Reactive balance training can also be task-specific by closely matching training to specific types of perturbations, including real-life fall incidence scenarios with which people may encounter during daily life (Gerards et al., 2017; Mansfield et al., 2015; McCrum et al., 2017). For example, tripping and slipping are often targeted given their high prevalence in inducing falls (Allin et al., 2020; Aviles et al., 2019; Mansfield et al., 2015).

Numerous studies have employed task-specific PBT. One example is so-called trip training to reduce the risk of trip-induced falls. These studies have employed different ways to implement trip training, which include perturbation from standing, perturbation while walking overground, and perturbation while walking on a treadmill. Grabiner et al. (2012) examined the effects of treadmill-induced postural perturbations from standing position among community-dwelling middle age and older women. The outcome assessment involved exposing participants to a laboratory-induced trip while walking on a walkway. Compared to the control group who received no training, the trip training group showed 22% fewer falls, 43% decrease in trunk flexion angle at recovery step completion, and 362% increase in trunk extension velocity at recovery step completion after the laboratory-induced trip. Wang et al. (2020) investigated the effects of repeated obstacle-induced trip training while walking on a walkway among community-dwelling older adults. The outcome assessment was obstacle-induced trips in laboratory over the course of training during which mixed blocks of trip and normal walking trials were performed. While 48% of the participants fell during the first trip trial, none of the participants fell during the last trip trial. The training effect was also retained after a 30-min retention interval (i.e., no difference in fall rates between the last trip trial during training and the trip trial after the retention period). In addition, this trip training led to improvements in proactive balance (i.e., reduced center-of-mass velocity and higher toe clearance) and reactive balance (i.e., decreased forward instability and reduced forward trunk rotation at recovery step). Sessoms et al. (2014) assessed the feasibility of treadmill-induced postural perturbations while walking on a treadmill as a potential trip-related fall risk assessment and training tool among U.S. military active-duty members who were with unilateral lower limb amputation, but a highly functional male aged 18-40 years. The outcome assessment measured peak trunk flexion angle and velocity during the initial recovery step following the perturbation. The peak trunk flexion angle and velocity were 31 deg and 131 deg/s smaller when participants recovered from treadmill-induced trip-like postural perturbations, as compared to when participants fell. These results supported the utility of such treadmill-induced postural perturbations while walking on a treadmill as a potential tool to assess trip-related fall risk and reduce trip-induced falls.

1.3. Limitations of Past Research

As described above, task-specific PBT such as trip training has shown promising results as an effective intervention to reduce fall rates and improve reactive balance after tripping. However, there are limitations that may hinder training adoption and widespread use. First, most trip training protocols use specialized treadmills that have significant cost requirements (Gerards et al., 2017; Mansfield et al., 2015; McCrum et al., 2017). These treadmills and any associated equipment (e.g., gantry for fall protection during training) require non-trivial space resources and can be cumbersome to move, if necessary. In addition, operators of these specialized treadmills require some level of technical training to operate the equipment. These requirements result in barriers for adoption by organizations and limit its widespread use.

Furthermore, researchers have traditionally used reflective markers and optical motion capture (OMC) systems to investigate reactive balance after laboratory-induced trips. (Allin et al., 2020; Crenshaw et al., 2013; Okubo et al., 2019; Pavol et al., 2001; Pijnappels et al., 2005). Although these systems are considered the gold standard for capturing body kinematics in biomechanics research, they require significant financial and space resources that can be barriers to their procurement and use. OMC systems also require setting up multiple cameras in a fixed location, which makes it difficult to conduct research outside a laboratory setting.

Lastly, numerous laboratory studies have induced trips among older adults to identify factors affecting trip recovery (Garman et al., 2015; Pater et al., 2016; Rosenblatt & Madigan, 2021), explore the biomechanical mechanisms underlying trip-induced falls (Pavol et al., 2001; Pijnappels et al., 2005; Van Dieen et al., 2005), and evaluate the efficacy of interventions aiming to reduce the prevalence of trip-induced falls (Aviles et al., 2019; Bieryla et al., 2007; Grabiner et al., 2012; Song et al., 2021; Wang et al., 2020). However, translation of these laboratory findings to real world (i.e., outside a research laboratory setting and during daily life) remains unclear because tripping scenarios, such as environmental or behavioral variations, in the real world are expected be more varied and diverse than those in a controlled laboratory tripping study.

1.4. Conclusion

Many exercised-based fall prevention interventions have been proposed, evaluated, and implemented to address risk factors for falls among older adults. Recent studies have demonstrated great promise for PBT using specialized treadmills, likely due to its greater specificity with respect to fall prevention than other forms of interventions. However, the cost requirements of specialized treadmills to implement such training are likely to limit its widespread use outside of the research setting. A less costly non-treadmill-based fall prevention intervention may promote adoption and accessibility of PBT. Furthermore, prior studies have used marker-based OMC systems to examine reactive balance after tripping. Despite their high accuracy, OMC systems are costly and cumbersome to set up. As an alternative, wearable inertial measurement units (IMUs) may provide quantitative kinematic data with reduced costs and space needs. Lastly, translation of laboratory-based findings from prior trip studies to real world remains unclear. Wearable IMUs can facilitate a direct comparison in tripping kinematics between the laboratory and real-world. Such a comparison may help fill existing knowledge gaps and provide directions for future trip studies.

References

Allin, L. J., Brolinson, P. G., Beach, B. M., Kim, S., Nussbaum, M. A., Roberto, K. A., & Madigan, M. L. (2020). Perturbation-based balance training targeting both slip-and trip-induced falls among older adults: a randomized controlled trial. *BMC geriatrics, 20*(1), 1-13.

Allin, L. J., Nussbaum, M. A., & Madigan, M. L. (2018). Feet kinematics upon slipping discriminate between recoveries and three types of slip-induced falls. *Ergonomics, 61*(6), 866-876.

Aviles, J., Allin, L. J., Alexander, N. B., Van Mullekom, J., Nussbaum, M. A., & Madigan, M. L. (2019). Comparison of treadmill trip-like training versus tai chi to improve reactive balance among independent older adult residents of senior housing: a pilot controlled trial. *The Journals of Gerontology: Series A, 74*(9), 1497-1503.

Bachman, J. C. (1961). Specificity vs. generality in learning and performing two large muscle motor tasks. *Research Quarterly. American Association for Health, Physical Education and Recreation, 32*(1), 3-11.

Begg, R., Best, R., Dell'Oro, L., & Taylor, S. (2007). Minimum foot clearance during walking: strategies for the minimisation of trip-related falls. *Gait & Posture, 25*(2), 191-198.

Berg, W. P., Alessio, H. M., Mills, E. M., & Tong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and Ageing, 26*(4), 261-268.

Bergen, G., Stevens, M. R., & Burns, E. R. (2016). Falls and fall injuries among adults aged≥ 65 years—United States, 2014. *Morbidity and Mortality Weekly Report, 65*(37), 993-998.

Bieryla, K. A., Madigan, M. L., & Nussbaum, M. A. (2007). Practicing recovery from a simulated trip improves recovery kinematics after an actual trip. *Gait & Posture, 26*(2), 208-213.

Bird, M. L., Hill, K., Ball, M., & Williams, A. D. (2009, Oct). Effects of Resistance- and Flexibility-Exercise Interventions on Balance and Related Measures in Older Adults [Article]. *Journal of aging and physical activity, 17*(4), 444-454. https://doi.org/10.1123/japa.17.4.444

Blake, A., Morgan, K., Bendall, M., Dallosso, H., Ebrahim, S., Arie, T. a., Fentem, P., & Bassey, E. (1988). Falls by elderly people at home: prevalence and associated factors. *Age and Ageing, 17*(6), 365-372.

Buchner, D. M., Cress, M. E., deLateur, B. J., Esselman, P. C., Margherita, A. J., Price, R., & Wagner, E. H. (1997a, Feb-Apr). A comparison of the effects of three types of endurance training on balance and other fall risk factors in older adults [Article]. *Aging clinical and experimental research, 9*(1-2), 112-119. https://doi.org/10.1007/bf03340136

Buchner, D. M., Cress, M. E., deLateur, B. J., Esselman, P. C., Margherita, A. J., Price, R., & Wagner, E. H. (1997b, Jul). The effect of strength and endurance training on gait, balance, fall risk, and health services use in community-living older adults [Article]. *Journals of Gerontology Series a-Biological Sciences and Medical Sciences, 52*(4), M218-M224. https://doi.org/10.1093/gerona/52A.4.M218

Campbell, A. J., Robertson, M. C., Gardner, M. M., Norton, R. N., & Buchner, D. M. (1999). Falls prevention over 2 years: a randomized controlled trial in women 80 years and older. *Age and Ageing, 28*(6), 513-518.

Campbell, A. J., Robertson, M. C., La Grow, S. J., Kerse, N. M., Sanderson, G. F., Jacobs, R. J., Sharp, D. M., & Hale, L. A. (2005). Randomised controlled trial of prevention of falls in people aged≥ 75 with severe visual impairment: the VIP trial. *Bmj, 331*(7520), 817. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1246082/pdf/bmj33100817.pdf

Centers for Disease Control and Prevention. (2017). *Leading Causes of Death Charts*. https://www.cdc.gov/injury/wisqars/LeadingCauses.html

Cham, R., & Redfern, M. S. (2001). Lower extremity corrective reactions to slip events. *Journal of Biomechanics, 34*(11), 1439-1445.

Chang, W.-R., Leclercq, S., Lockhart, T. E., & Haslam, R. (2016). State of science: occupational slips, trips and falls on the same level. *Ergonomics, 59*(7), 861-883.

Cigolle, C. T., Ha, J., Min, L. C., Lee, P. G., Gure, T. R., Alexander, N. B., & Blaum, C. S. (2015). The epidemiologic data on falls, 1998-2010: more older Americans report falling. *Jama Internal Medicine, 175*(3), 443-445.

Claudino, J. G., Afonso, J., Sarvestan, J., Lanza, M. B., Pennone, J., Filho, C. A. C., Serrao, J. C., Espregueira-Mendes, J., Vasconcelos, A. L. V., de Andrade, M. P., Rocha-Rodrigues, S., Andrade, R., & Ramirez-Campillo, R. (2021, Jul). Strength Training to Prevent Falls in Older Adults: A Systematic Review with Meta-Analysis of Randomized Controlled Trials. *Journal of clinical medicine, 10*(14), Article 3184. https://doi.org/10.3390/jcm10143184

Clemson, L., Cumming, R. G., Kendig, H., Swann, M., Heard, R., & Taylor, K. (2004). The effectiveness of a community-based program for reducing the incidence of falls in the elderly: A randomized trial. *Journal of the American Geriatrics Society, 52*(9), 1487-1494.

Crenshaw, J. R., Kaufman, K. R., & Grabiner, M. D. (2013). Trip recoveries of people with unilateral, transfemoral or knee disarticulation amputations: Initial findings. *Gait & Posture, 38*(3), 534-536.

Cumming, R. G., Thomas, M., Szonyi, G., Salkeld, G., O'Neill, E., Westbury, C., & Frampton, G. (1999). Home visits by an occupational therapist for assessment and modification of environmental hazards: a randomized trial of falls prevention. *Journal of the American Geriatrics Society, 47*(12), 1397-1402.

Davison, J., Bond, J., Dawson, P., Steen, I. N., & Kenny, R. A. (2005). Patients with recurrent falls attending Accident & Emergency benefit from multifactorial intervention—a randomised controlled trial. *Age and Ageing, 34*(2), 162-168.

Florence, C. S., Bergen, G., Atherly, A., Burns, E., Stevens, J., & Drake, C. (2018). Medical costs of fatal and nonfatal falls in older adults. *Journal of the American Geriatrics Society, 66*(4), 693-698.

Garman, C. R., Franck, C. T., Nussbaum, M. A., & Madigan, M. L. (2015). A bootstrapping method to assess the influence of age, obesity, gender, and gait speed on probability of tripping as a function of obstacle height. *Journal of Biomechanics, 48*(6), 1229-1232.

Gerards, M. H., McCrum, C., Mansfield, A., & Meijer, K. (2017). Perturbation-based balance training for falls reduction among older adults: Current evidence and implications for clinical practice. *Geriatrics & Gerontology International, 17*(12), 2294-2303.

Gliner, J. A. (1985). Purposeful activity in motor learning theory: An event approach to motor skill acquisition. *American Journal of Occupational Therapy, 39*(1), 28-34.

Grabiner, M. D., Bareither, M. L., Gatts, S., Marone, J., & Troy, K. L. (2012). Task-specific training reduces trip-related fall risk in women.

Grabiner, M. D., Crenshaw, J. R., Hurt, C. P., Rosenblatt, N. J., & Troy, K. L. (2014). Exercise-based fall prevention: can you be a bit more specific? *Exercise and sport sciences reviews, 42*(4), 161-168.

Grabiner, M. D., Koh, T. J., Lundin, T. M., & Jahnigen, D. W. (1993). Kinematics of recovery from a stumble. *Journal of gerontology, 48*(3), M97-M102.

Granacher, U., Muehlbauer, T., Gollhofer, A., Kressig, R. W., & Zahner, L. (2011). An intergenerational approach in the promotion of balance and strength for fall prevention–a mini-review. *Gerontology, 57*(4), 304-315.

Granacher, U., Muehlbauer, T., & Gruber, M. (2012). A Qualitative Review of Balance and Strength Performance in Healthy Older Adults: Impact for Testing and Training. *Journal of Aging Research, 2012*, 1-16. https://doi.org/10.1155/2012/708905

Gusi, N., Adsuar, J. C., Corzo, H., del Pozo-Cruz, B., Olivares, P. R., & Parraca, J. A. (2012). Balance training reduces fear of falling and improves dynamic balance and isometric strength in institutionalised older people: a randomised trial. *Journal of physiotherapy, 58*(2), 97-104. https://doi.org/10.1016/s1836-9553(12)70089-9

Harwood, R. H., Foss, A., Osborn, F., Gregson, R., Zaman, A., & Masud, T. (2005). Falls and health status in elderly women following first eye cataract surgery: a randomised controlled trial. *British Journal of Ophthalmology*, *89*(1), 53-59. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1772474/pdf/bjo08900053.pdf

Houry, D., Florence, C., Baldwin, G., Stevens, J., & McClure, R. (2016). The CDC Injury Center's response to the growing public health problem of falls among older adults. *American journal of lifestyle medicine, 10*(1), 74-77.

Hu, Y.-N., Chung, Y.-J., Yu, H.-K., Chen, Y.-C., Tsai, C.-T., & Hu, G.-C. (2016). Effect of Tai Chi exercise on fall prevention in older adults: systematic review and meta-analysis of randomized controlled trials. *International Journal of Gerontology, 10*(3), 131-136.

Hubbard, I. J., Parsons, M. W., Neilson, C., & Carey, L. M. (2009). Task-specific training: evidence for and translation to clinical practice. *Occupational therapy international, 16*(3-4), 175-189.

Kunzler, M. R., da Rocha, E. S., Dos Santos, C. S., Ceccon, F. G., Priario, L. A., & Carpes, F. P. (2018). Should we consider steps with variable height for a safer stair negotiation in older adults? *Work*, *59*(1), 15-21. https://content.iospress.com/articles/work/wor2658

Lan, C., Chen, S.-Y., Lai, J.-S., & Wong, A. M.-K. (2013). Tai chi chuan in medicine and health promotion. *Evidence-based complementary and alternative medicine, 2013*.

Lesinski, M., Hortobágyi, T., Muehlbauer, T., Gollhofer, A., & Granacher, U. (2015). Effects of Balance Training on Balance Performance in Healthy Older Adults: A Systematic Review and Meta-analysis. *Sports Medicine*, *45*(12), 1721-1738. https://doi.org/10.1007/s40279-015-0375-y

Leung, D. P., Chan, C. K., Tsang, H. W., Tsang, W. W., & Jones, A. Y. (2011). Tai chi as an intervention to improve balance and reduce falls in older adults: A systematic and meta-analytical review. *Alternative Therapies in Health & Medicine, 17*(1).

Lipscomb, H. J., Glazner, J. E., Bondy, J., Guarini, K., & Lezotte, D. (2006). Injuries from slips and trips in construction. *Applied ergonomics, 37*(3), 267-274.

Liu-Ambrose, T., Khan, K. M., Eng, J. J., Janssen, P. A., Lord, S. R., & Mckay, H. A. (2004). Resistance and agility training reduce fall risk in women aged 75 to 85 with low bone mass: A 6-month randomized, controlled trial. *Journal of the American Geriatrics Society, 52*(5), 657-665.

Logan, P. A., Coupland, C. A., Gladman, J. R., Sahota, O., Stoner-Hobbs, V., Robertson, K., Tomlinson, V., Ward, M., Sach, T., & Avery, A. J. (2010). Community falls prevention for people who call an emergency ambulance after a fall: randomised controlled trial. *Bmj, 340*, c2102. https://www.bmj.com/content/bmj/340/bmj.c2102.full.pdf

Logghe, I. H., Verhagen, A. P., Rademaker, A. C., Bierma-Zeinstra, S. M., van Rossum, E., Faber, M. J., & Koes, B. W. (2010). The effects of Tai Chi on fall prevention, fear of falling and balance in older people: a meta-analysis. *Preventive medicine, 51*(3-4), 222-227.

Luchies, C. W., Wallace, D., Pazdur, R., Young, S., & DeYoung, A. J. (1999). Effects of age on balance assessment using voluntary and involuntary step tasks. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences, 54*(3), M140-M144.

Lurie, J. D., Zagaria, A. B., Pidgeon, D. M., Forman, J. L., & Spratt, K. F. (2013). Pilot comparative effectiveness study of surface perturbation treadmill training to prevent falls in older adults. *BMC geriatrics, 13*(1), 1-8.

Luukinen, H., Herala, M., Koski, K., Honkanen, R., Laippala, P., & Kivelä, S.-L. (2000). Fracture risk associated with a fall according to type of fall among the elderly. *Osteoporosis International, 11*(7), 631-634. https://link.springer.com/content/pdf/10.1007/s001980070086.pdf

Madureira, M. M., Takayama, L., Gallinaro, A. L., Caparbo, V. F., Costa, R. A., & Pereira, R. M. R. (2007). Balance training program is highly effective in improving functional status and reducing the risk of falls in elderly women with osteoporosis: a randomized controlled trial. *Osteoporosis International, 18*(4), 419-425. https://doi.org/10.1007/s00198-006-0252-5

Mansfield, A., Aqui, A., Danells, C. J., Knorr, S., Centen, A., Depaul, V. G., Schinkel-Ivy, A., Brooks, D., Inness, E. L., & Mochizuki, G. (2018). Does perturbation-based balance training prevent falls among individuals with chronic stroke? A randomised controlled trial. *BMJ open, 8*(8), e021510. https://doi.org/10.1136/bmjopen-2018-021510

Mansfield, A., Peters, A. L., Liu, B. A., & Maki, B. E. (2010). Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: a randomized controlled trial. *Physical Therapy, 90*(4), 476-491.

Mansfield, A., Wong, J. S., Bryce, J., Knorr, S., & Patterson, K. K. (2015). Does perturbation-based balance training prevent falls? Systematic review and meta-analysis of preliminary randomized controlled trials. *Physical Therapy, 95*(5), 700-709.

Marigold, D. S., Bethune, A. J., & Patla, A. E. (2003). Role of the unperturbed limb and arms in the reactive recovery response to an unexpected slip during locomotion. *Journal of neurophysiology, 89*(4), 1727-1737.

Martins, A. C., Santos, C., Silva, C., Baltazar, D., Moreira, J., & Tavares, N. (2018). Does modified Otago Exercise Program improves balance in older people? A systematic review. *Preventive medicine reports, 11*, 231-239.

McCrum, C., Gerards, M. H., Karamanidis, K., Zijlstra, W., & Meijer, K. (2017). A systematic review of gait perturbation paradigms for improving reactive stepping responses and falls risk among healthy older adults. *European Review of Aging and Physical Activity, 14*(1), 1-11.

Murray, C. J., Vos, T., Lozano, R., Naghavi, M., Flaxman, A. D., Michaud, C., Ezzati, M., Shibuya, K., Salomon, J. A., & Abdalla, S. (2012). Disability-adjusted life years (DALYs) for 291 diseases and injuries in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet, 380*(9859), 2197-2223.

Okubo, Y., Schoene, D., & Lord, S. R. (2017). Step training improves reaction time, gait and balance and reduces falls in older people: a systematic review and meta-analysis. *British Journal of Sports Medicine, 51*(7), 586-593.

Okubo, Y., Sturnieks, D. L., Brodie, M. A., Duran, L., & Lord, S. R. (2019, Aug 16). Effect of Reactive Balance Training Involving Repeated Slips and Trips on Balance Recovery Among Older Adults: A Blinded Randomized Controlled Trial. *J Gerontol A Biol Sci Med Sci, 74*(9), 1489-1496. https://doi.org/10.1093/gerona/glz021

Owings, T. M., Pavol, M. J., & Grabiner, M. D. (2001). Mechanisms of failed recovery following postural perturbations on a motorized treadmill mimic those associated with an actual forward trip. *Clinical Biomechanics, 16*(9), 813-819.

Pai, Y.-C., Bhatt, T., Yang, F., Wang, E., & Kritchevsky, S. (2014). Perturbation training can reduce community-dwelling older adults' annual fall risk: a randomized controlled trial. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences, 69*(12), 1586-1594. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4296119/pdf/glu087.pdf

Pater, M. L., Rosenblatt, N. J., & Grabiner, M. D. (2016, May 3). Knee osteoarthritis negatively affects the recovery step following large forward-directed postural perturbations. *J Biomech, 49*(7), 1128-1133. https://doi.org/10.1016/j.jbiomech.2016.02.048

Pavol, M. J., Owings, T. M., Foley, K. T., & Grabiner, M. D. (2001). Mechanisms Leading to a Fall From an Induced Trip in Healthy Older Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 56*(7), M428-M437.

Pfortmueller, C., Lindner, G., & Exadaktylos, A. (2014). Reducing fall risk in the elderly: risk factors and fall prevention, a systematic review. *Minerva Med, 105*(4), 275-281.

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2005). Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. *Gait & Posture, 21*(4), 388-394.

Prata, M. G., & Scheicher, M. E. (2015, Oct). Effects of strength and balance training on the mobility, fear of falling and grip strength of elderly female fallers. *Journal of Bodywork and Movement Therapies, 19*(4), 646-650. https://doi.org/10.1016/j.jbmt.2014.11.013

Redfern, M. S., Cham, R., Gielo-Perczak, K., Grönqvist, R., Hirvonen, M., Lanshammar, H., Marpet, M., Pai IV, C. Y.-C., & Powers, C. (2001). Biomechanics of slips. *Ergonomics, 44*(13), 1138-1166. https://www.tandfonline.com/doi/abs/10.1080/00140130110085547

Rosenblatt, N. J., & Madigan, M. L. (2021). Exploring the association between measures of obesity and measures of trip-induced fall risk among older adults. *Archives of Physical Medicine and Rehabilitation*.

Sakamoto, K., Nakamura, T., Hagino, H., Endo, N., Mori, S., Muto, Y., Harada, A., Nakano, T., Itoi, E., & Yoshimura, M. (2006). Effects of unipedal standing balance exercise on the prevention of falls and hip fracture among clinically defined high-risk elderly individuals: a randomized controlled trial. *Journal of Orthopaedic Science, 11*(5), 467-472.

Schoene, D., Lord, S. R., Delbaere, K., Severino, C., Davies, T. A., & Smith, S. T. (2013). A randomized controlled pilot study of home-based step training in older people using videogame technology. *Plos One, 8*(3), e57734.

Sessoms, P. H., Wyatt, M., Grabiner, M., Collins, J.-D., Kingsbury, T., Thesing, N., & Kaufman, K. (2014). Method for evoking a trip-like response using a treadmill-based perturbation during locomotion. *Journal of Biomechanics, 47*(1), 277-280. https://doi.org/10.1016/j.jbiomech.2013.10.035

Sherrington, C., Michaleff, Z. A., Fairhall, N., Paul, S. S., Tiedemann, A., Whitney, J., Cumming, R. G., Herbert, R. D., Close, J. C., & Lord, S. R. (2017). Exercise to prevent falls in older adults: an updated systematic review and meta-analysis. *British Journal of Sports Medicine, 51*(24), 1750-1758.

Shigematsu, R., & Okura, T. (2006). A novel exercise for improving lower-extremity functional fitness in the elderly. *Aging clinical and experimental research, 18*(3), 242-248.

Song, P. Y., Sturnieks, D. L., Davis, M. K., Lord, S. R., & Okubo, Y. (2021). Perturbation-Based Balance Training Using Repeated Trips on a Walkway vs. Belt Accelerations on a Treadmill: A Cross-Over Randomised Controlled Trial in Community-Dwelling Older Adults. *Frontiers in Sports and Active Living, 3*.

Steadman, J., Donaldson, N., & Kalra, L. (2003). A randomized controlled trial of an enhanced balance training program to improve mobility and reduce falls in elderly patients. *Journal of the American Geriatrics Society, 51*(6), 847-852.

Stevens, J. A., Mahoney, J. E., & Ehrenreich, H. (2014). Circumstances and outcomes of falls among high risk community-dwelling older adults. *Injury Epidemiology, 1*(1), 5.

Strandberg, L. (1983). On accident analysis and slip-resistance measurement. *Ergonomics, 26*(1), 11-32.

Takacs, J., Carpenter, M. G., Garland, S. J., & Hunt, M. A. (2013). The role of neuromuscular changes in aging and knee osteoarthritis on dynamic postural control. *Aging and disease, 4*(2), 84.

Thomas, S., Mackintosh, S., & Halbert, J. (2010). Does the 'Otago exercise programme' reduce mortality and falls in older adults?: a systematic review and meta-analysis. *Age and Ageing, 39*(6), 681-687. https://doi.org/10.1093/ageing/afq102

Tinetti, M. E., & Kumar, C. (2010). The patient who falls:"It's always a trade-off". *Jama, 303*(3), 258-266.

Troy, K. L., & Grabiner, M. D. (2007). Asymmetrical ground impact of the hands after a trip-induced fall: Experimental kinematics and kinetics. *Clinical Biomechanics, 22*(10), 1088-1095. https://doi.org/10.1016/j.clinbiomech.2007.07.014

Van Dieen, J. H., Pijnappels, M., & Bobbert, M. (2005). Age-related intrinsic limitations in preventing a trip and regaining balance after a trip. *Safety science, 43*(7), 437-453.

Wang, C., Collet, J. P., & Lau, J. (2004). The effect of Tai Chi on health outcomes in patients with chronic conditions: a systematic review. *Archives of internal medicine, 164*(5), 493-501.

Wang, Y., Wang, S., Bolton, R., Kaur, T., & Bhatt, T. (2020). Effects of task-specific obstacle-induced trip-perturbation training: proactive and reactive adaptation to reduce fall-risk in community-dwelling older adults. *Aging clinical and experimental research, 32*(5), 893-905.

Winter, D. A. (1992). Foot trajectory in human gait: a precise and multifactorial motor control task. *Physical Therapy, 72*(1), 45-53.

Yang, F., Espy, D., Bhatt, T., & Pai, Y.-C. (2012). Two types of slip-induced falls among community dwelling older adults. *Journal of Biomechanics, 45*(7), 1259-1264. https://doi.org/10.1016/j.jbiomech.2012.01.036

Yoon, H.-Y., & Lockhart, T. E. (2006). Nonfatal occupational injuries associated with slips and falls in the United States. *International Journal of Industrial Ergonomics, 36*(1), 83-92.

Chapter 2. Effects of Non-Treadmill Trip Training on Reactive Balance after Laboratory-Induced Trips among Community-Dwelling Older Adults

2.1. Introduction

Falls are the leading cause of injuries among adults aged 65 years or older in the United States (Bergen et al., 2016; Centers for Disease Control and Prevention, 2017). These falls are costly with annual medical expenditures of $50 billion (Florence et al., 2018). A large number of falls experienced by older adults are due to an age-related decline in reactive balance after a trip-induced loss of balance (LOB) (Berg et al., 1997; Pavol et al., 1999; Stevens et al., 2014; Van Dieen et al., 2005). Perturbation-based balance training (PBT) has received growing interest as a fall prevention intervention (Gerards et al., 2017; Mansfield, Wong, et al., 2015; Okubo et al., 2017), with the goal of improving this reactive balance ability. In fact, a growing number of studies have shown that PBT targeting trips improves reactive balance after laboratory-induced trips (Bieryla et al., 2007; Grabiner et al., 2012; Wang et al., 2020) and decrease fall rates after real-world trips (Rosenblatt et al., 2013). Past studies have implemented this so-called trip training by simulating trips using treadmill perturbations from standing (Aviles et al., 2019; Grabiner et al., 2012), obstacle-induced perturbations while walking overground (Wang et al., 2020), and treadmill perturbations while walking on a treadmill (Pinata H. Sessoms et al., 2014).

Potential barriers to the wider application of treadmill-based trip training (Aviles et al., 2019; Bieryla et al., 2007; Kaufman et al., 2014; Lurie et al., 2013; Pigman et al., 2019; Pinata H. Sessoms et al., 2014; Song et al., 2021) include the cost and space requirements of a treadmill (Aviles et al., 2020). A trip training regimen that does not require a treadmill may facilitate the use of this training outside the research setting. In a review, Gerards et al. (2017) described alternative

PBT methods used in prior studies among older adults with stroke (Mansfield, Aqui, et al., 2015; Mansfield et al., 2017; Marigold et al., 2005). These methods include rapid voluntary movements that involve progressive balance challenges (e.g., multidirectional stepping with obstacles) and manually-applied perturbations that require reactive stepping to maintain balance (e.g., lean-and-release, pushing or pulling). Adapting these general perturbations to specifically target reactive balance after tripping may enable trip training without the costs and space needs associated with a treadmill.

The purpose of this study was to investigate the effects of a task-specific, non-treadmill-based trip training regimen on reactive balance among community-dwelling older adults. For comparison, separate groups of participants completed treadmill-based trip training or a control (i.e., no training). We first hypothesized that non-treadmill training (NT) participants and treadmill training (TT) participants will exhibit improved fall rates and reactive balance after laboratory-induced trips compared to control group (CG) participants. This hypothesis was based upon the previous TT studies showing improved fall rates and reactive balance after laboratory-induced trips (Gerards et al., 2017; Grabiner et al., 2014; Mansfield, Wong, et al., 2015). Similar findings were expected for NT because both NT and TT specifically aim to improve several important movements for successful balance recovery after tripping. We also hypothesized that TT participants will exhibit a lower fall rate and better reactive balance after laboratory-induced trips compared to NT participants. This hypothesis was based on the statement from a systematic review and meta-analysis (Okubo et al., 2017) that a greater balance challenge may lead to a greater stimulus for learning how to avert a fall. Since TT involves responses to larger, more sudden trip-like perturbations than NT, greater improvements were expected from TT than NT. If efficacious, NT could provide a lower cost method for PBT targeting trip-induced falls and facilitate greater application outside of the research environment.

2.2. Methods

Thirty community-dwelling older adults (Figure 2.1) completed the study (12 M and 18 F; mean [SD] age: 71.8 [4.4] years; height: 1.68 [0.10] m; mass: 77.1 [16.8] kg; and unipedal stance time:17.6 [12.3] sec). Participants were recruited from the university and local community via email listservs, flyers, word-of-mouth, and visits to local community organizations. Inclusion criteria required participants to be aged 65-80 years, have no lower limb amputation, weigh ≤ 250 lbs, not use a walker, not be dependent on using a cane all the time, and not regularly do any kind of exercise to improve balance (e.g., Tai Chi). Participants were also required to pass a health screening questionnaire reviewed by a health care specialist informed of the physical requirements of the study. Exclusion criteria explicitly used in this questionnaire included: a history of hip or vertebral fracture; current back, leg, or foot pain that interfered with standing or walking; hospitalization within the last six months; score ≤ 18 on the Montreal Cognitive Assessment – Blind (Wittich et al., 2010); and osteoporosis of the lumbar spine or proximal femur as indicated by bone mineral density of *t*-score < -2.5 obtained from Dual Energy X-ray Absorptiometry (Lunar iDXA, GE Healthcare, Chicago, IL). The study was approved by the Virginia Tech Institutional Review Board, and all participants provided written consent prior to participation.

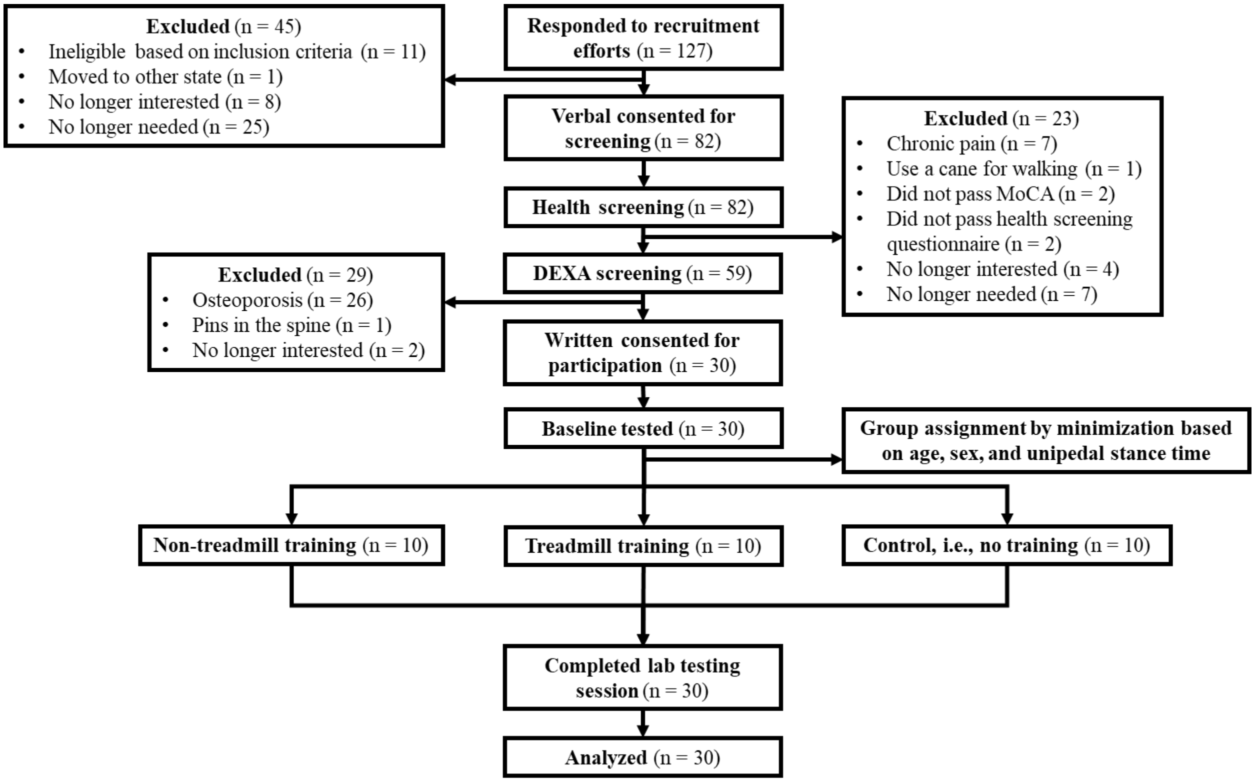

Figure 2.1. Protocol flow diagram showing participant enrollment, exclusion, and allocation. MoCA = Montreal Cognitive Assessment. DEXA = Dual-Energy X-ray Absorptiometry.

The sample size was determined using trunk flexion angle data after laboratory-induced trips among middle age and older women from Grabiner et al. (2012) and following the procedure of UCLA Statistical Consulting Group (2021). The effect size *f*-statistic for an analysis involving three groups was calculated with G*Power (Faul et al., 2007) using means of 37 deg (falls), 22 deg (recoveries), and 30 deg (mean of falls and recoveries). The standard deviation was set to 9 deg (across falls and recoveries). Using trunk flexion angles of falls and recoveries reported by Grabiner et al. (2012) for these means is an example of the anchor-based method for estimating the minimum important difference (Rai et al., 2015). Based on a one-way analysis of variance and *a priori* power analysis using 80% power and 5% Type I error, a sample size of 27 participants was needed across the three groups. To account for potential dropouts, this estimate was increased 10%, resulting in a total of 30 participants (i.e., 10 participants per group) being recruited.

A three-group post-test design was used. Participants were first assigned to either NT (n=10), TT (n=10), or CG (n=10) using minimization (Altman & Bland, 2005; Taves, 1974) to balance groups with respect to age, sex, and unipedal stance time (Table 2.1). NT and TT participants completed two 45-minute training sessions per week over three weeks in our research laboratory (i.e., a total of six training sessions). A multi-day training regimen individualized to each participant's capability was used to improve LOB responses while building confidence and lowering anxiety levels from gradual training progressions (Gerards et al., 2017; Okubo et al., 2019). Each of these sessions included an active training time of 30 minutes of the assigned intervention. CG participants completed no training. After the completion of training, all participants attended an outcome assessment session during which they were exposed to two laboratory-induced trips while walking on a walkway. To characterize our sample and evaluate any changes due to the assigned intervention, clinical tests of balance and mobility were conducted during the first training session and the outcome assessment session before the trips. These tests included the timed-up-and-go test (Shumway-Cook et al., 2000), unipedal stance time (Vellas et al., 1997), 3-m overground walk test with walking start and a purposeful speed (Sustakoski et al., 2015), and Berg Balance Scale (Berg et al., 1992).

Table 2.1. Participant characteristics. Values are the counts or arithmetic means (standard deviations). One-way analysis of variance with group as the independent variable was used to compute *p*-value.

	NT (n=10)	TT (n=10)	CG (n=10)	*p*-value
Sex (male / female)	4 / 6	4 / 6	4 / 6	-
Age (years)	71.9 (4.1)	71.8 (5.2)	71.8 (4.3)	0.998
Unipedal stance time (s)	18.9 (11.5)	16.5 (12.7)	17.3 (13.8)	0.917
Height (m)	1.63 (0.08)	1.69 (0.10)	1.70 (0.12)	0.277
Mass (kg)	69.9 (17.0)	79.6 (15.8)	81.9 (16.8)	0.244
Number of participants reporting one or more falls over prior six months	1	3	1	-

Details of the NT protocol have been published (Lee et al., 2022). Specifically, it targets to improve three requisites for balance recovery after tripping, which include limiting trunk flexion, taking a long recovery step, and maintaining sufficient hip height (Owings et al., 2001; Pavol et al., 2001; Pijnappels et al., 2005; Van Dieen et al., 2005). Each NT session began with a three-minute warm-up of walking on a treadmill and light stretching. Then, it proceeded to active training consisting of four phases with increasing difficulty and similarity to actual trip recovery while walking. *Phase 1 – Rapid Stepping* involved volitional stepping exercises from bilateral standing, where the participant started to fall forward and then took quick steps to recover balance. The participant was encouraged to fall as far forward as possible before starting to step, and also to take a long initial recovery step. This exercise was performed first without a trip obstacle, and then with a trip obstacle with a height of 8.6 cm. *Phase 2 – Trunk Control* involved similar stepping exercises as Phase 1, but with explicit instructions and emphasis on arresting trunk motion and controlling trunk posture to be vertical at touchdown of the first recovery step. *Phase 3 – Lean Release* involved similar exercises as Phases 1 and 2, but with the addition of an "unexpected" forward

LOB. The participant leaned forward while being supported by the trainer with his/her hands on the participant's shoulders and his/her arms fully extended in front of the participant. Without warning, the trainer released the participant and stepped aside, and the participant took recovery steps to regain balance. *Phase 4 – Simulated Trip* involved self-inducing a trip and practicing stepping using the elevating strategy, which is the most common trip recovery strategy used after a trip (Eng et al., 1994). The participant stood 6-12 inches away from the trip obstacle, stepped toward the obstacle, purposefully tripped on the obstacle, started to fall forward, elevated the obstructed foot over the obstacle to recover balance, and then continued walking. Such an exercise was repeated, while emphasizing on taking a long initial recovery step and controlling trunk posture to be vertical at touchdown of the first recovery step. NT was administered one participant at a time, and all phases were individualized to each participant's capability and rate of improvement to continuously challenge the participant. To prevent a fall in the event of an unsuccessful balance recovery, two trainers stood in front and side, respectively, of the participant and served as spotters. Additionally, during the first training session (and later session if requested by the participant), the participant wore a full body fall protection harness suspended from an overhead track while becoming familiar with the training protocol and gaining confidence in performing these stepping exercises.

The TT group completed trip training with a specialized treadmill (Aviles et al., 2019). TT perturbations were induced while the participant was standing on a modified treadmill (Freemotion 800, Freemotion Fitness, Logan, UT). The treadmill belt was then accelerated posteriorly, varying in speed from 0.8 to 2.4 mph, to induce a forward LOB within about 40 msec. Perturbations in the reverse belt direction (i.e., 0.8 mph anteriorly) were also included intermittently to reduce anticipation. Starting in the second training session, a slender, rectangular foam block (8.6 x 8.6 cm cross section) was placed within 3-7 cm in front of the participant's toes before each perturbation to elicit a step over an obstacle, similar to that needed during an actual trip. The participant was instructed to react naturally and try to establish a stable gait after perturbations (and an initial step over an obstacle, if used). The treadmill belt speed was maintained until one of two conditions was met: (1) the participant established a stable gait for several strides, or (2) the participant received substantial support from a fall protection harness or a spotter standing next to the participant. Based upon the performance of the participant, the treadmill speed was progressively increased during each session to continue challenging the participant and to maintain variability over the course of training. The participant wore a full body fall protection harness, which was supported by an overhead gantry, to protect knees or hands from contact with the treadmill in the event of an unsuccessful attempt to recover balance. Each TT session was one-on-one training where the participant was exposed to up to 40 treadmill perturbations with a 5-minute rest break after 20 perturbations.

After the completion of training, participants were exposed to two laboratory-induced trips while walking using methods described elsewhere (Allin et al., 2020; Garman et al., 2016). Briefly, participants first completed a minimum of 10 walking trials on a 12-meter level walkway where a trip obstacle was concealed and leveled with the walkway surface. These walking trials determined the appropriate starting location on the walkway to trip participants and to minimize expectation of the timing of the trip. Participants were asked to walk at a purposeful speed (i.e., as if they were going somewhere) while looking straight ahead. To interject some unexpectedness with respect to the timing of the trips, participants were informed that they may or may not be exposed to one or more unexpected trips or slips while walking, and if they experience one of these, simply react naturally and continue walking. After completing a minimum of 10 walking trials, the trip obstacle was activated and quickly rose to a height of 8.6 cm without warning at the start of the stance phase of the non-dominant foot to attempt to trip the dominant foot during its ensuing swing phase. Afterward, attempts were made to slip participants (reported elsewhere) and trip participants once more (within two additional attempts), each after a minimum of three walking trials. Participants wore standardized footwear (New Balance Athletics, Inc.) and a full body fall protection harness for their safety in the event of an unsuccessful balance recovery. The harness was attached to an overhead track with the length of lanyard adjusted so that the participant's knees, when asked to kneel while allowing the harness to fully support the body weight, were approximately 10 cm from the walkway surface.

During the trip trials, whole body kinematics were recorded by a 13-camera motion capture system (Qualisys North America, Inc., Buffalo Grove, IL) using 13 reflective markers placed at acromion processes (shoulders), xiphoid process, spine at the same height as xiphoid process (back), sacrum, greater trochanters (hips), tip of the second toes, lateral malleoli (ankles), and calcanei (heels). The marker data were sampled at 128 Hz and later low-pass filtered at 10 Hz (fourth-order, zero-phase-lag, Butterworth filter). Force applied to the fall protection harness was recorded using a uniaxial load cell (Cooper Instruments, Warrenton, VA). The force data were sampled at 1280 Hz and later low-pass filtered at 40 Hz (fourth-order, zero-phase-lag, Butterworth filter). Subsequent data processing was performed using custom code in MATLAB R2021a (The MathWorks Inc., Natick, MA).

For calculating outcome measures, two critical temporal events were first determined: trip onset (the time instant at which the tripped foot contacted the trip obstacle as indicated by the resultant acceleration of the midpoint of the three foot markers) and touchdown (the time instant at which the first recovery step over the trip obstacle contacted the walkway as indicated by the resultant acceleration of the midpoint of the three foot markers). The primary outcome measure was *trunk angle at touchdown* (sagittal plane angle determined by a line connecting midpoint of the hip markers and midpoint of the xiphoid process and back markers, relative to quiet standing). The secondary outcome measures included *recovery step length* (anterior-posterior distance between the ankle marker of the stance limb at trip onset and the ankle marker of the stepping foot at touchdown), *recovery step speed* (anterior-posterior speed determined by dividing the recovery step length by recovery step completion time), *Distance between mid-hips and step at touchdown* (anterior-posterior distance between the midpoint of the hip markers and toe marker at touchdown), and *sacrum height at touchdown* (vertical position of the sacrum marker at touchdown). In addition, *gait speed* (anterior-posterior speed of the midpoint of the shoulder markers at trip onset), *stepping strategy* (elevating or lowering based on the definitions from Eng et al. (1994)), and *trip outcome* were recorded. Each trip outcome was classified as either a fall, recovery, harness-assist, or missed trip based on the force applied to the fall protection harness and video review. A fall occurred if a participant was fully and continuously supported by the harness as observed from video. A recovery occurred if an integrated harness force (i.e., an impulse from trip onset to one second after touchdown) did not exceed 20% body weight * second. A harness-assist occurred if a trial was neither a fall nor recovery. A missed trip occurred if the leading edge of the swing foot did not contact the trip obstacle during mid-to-late swing phase, due to improper timing of triggering the trip obstacle.

Fisher's exact test was used to investigate differences in trip outcome and stepping strategy between groups. A mixed-model analysis of variance (ANOVA) with *a priori* pairwise contrasts was used to investigate differences in kinematic measures between groups, and included additional factors of trip number, trip outcome, stepping strategy, gait speed, and pre-training Berg Balance Scale score. Transformation of the outcome measures was performed when needed for residuals of the ANOVA model to approximate a normal distribution, and results were back-transformed to the original scale for reporting. A two-way ANOVA with *a priori* pairwise contrasts was used to investigate differences in clinical tests between groups and time (pre- vs. post-training). All statistical analyses were performed using JMP Pro 16 (SAS Institute, Inc., Cary, NC) with a significance level of 0.05.

2.3. Results

All 30 participants successfully completed their assigned training and outcome assessment. The 60 trip outcomes (two from each of the 30 participants) included 22 falls, 27 recoveries, 7 harness-assists, and 4 missed trips. Harness-assists and missed trips were excluded from further analysis. The mean (SD) gait speed across the included 49 trips was 1.54 (0.21) m/s. Fall rates among NT (24% of 17 trips; $p = 0.157$) and TT participants (63% of 16 trips; $p = 0.722$) did not differ from CG participants (50% from 16 trips) (Figure 2.2). Despite this, NT and TT participants exhibited improved reactive balance compared to CG participants (Figure 2.3). Recovery step length was 8.5% body height (BH) longer among NT participants compared to CG participants ($p = 0.002$). Recovery step speed was 0.21 m/s faster among NT participants compared to CG participants ($p = 0.022$). Trunk angle at touchdown was 5.5 deg smaller among TT participants compared to CG participants (p = 0.027) (see Tables A.1 and A.2 in Appendices for additional details of the results from the mixed-model ANOVA).

Between NT and TT participants, fall rate was 39% higher among TT participants compared to NT participants (p = 0.037) (Figure 2.2). Trunk angle at touchdown was 5.3 deg smaller among TT participants compared to NT participants (p = 0.039) (Figure 2.3). No other pairwise group differences in kinematics were found (see Tables A.1 and A.2 in Appendices for additional details of the results from the mixed-model ANOVA). Regarding the clinical tests, the 3-m overground walk test showed a main effect of group (p = 0.014). Our *a priori* pairwise contrasts indicated that pre-training 3-m overground walk test was completed 0.24 s and 0.22 s faster among NT participants compared to CG (p = 0.017) and TT (p = 0.027) participants, respectively. No other group or time differences in clinical tests were found (see Table A.3 in Appendices for additional details).

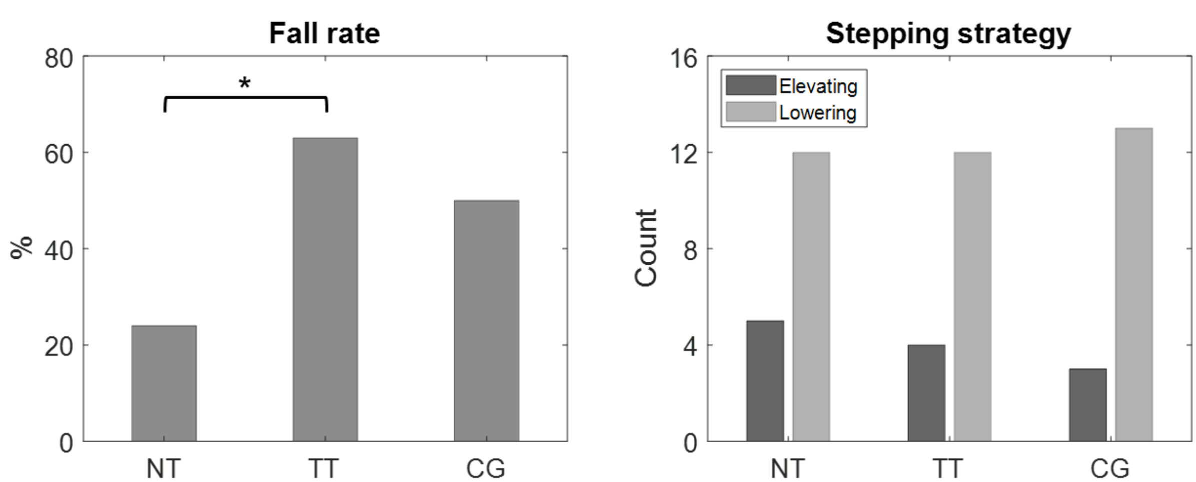

Figure 2.2. Summary of trip outcome (represented as fall rate) and stepping strategy across the three groups. Asterisk indicates statistically significant difference.

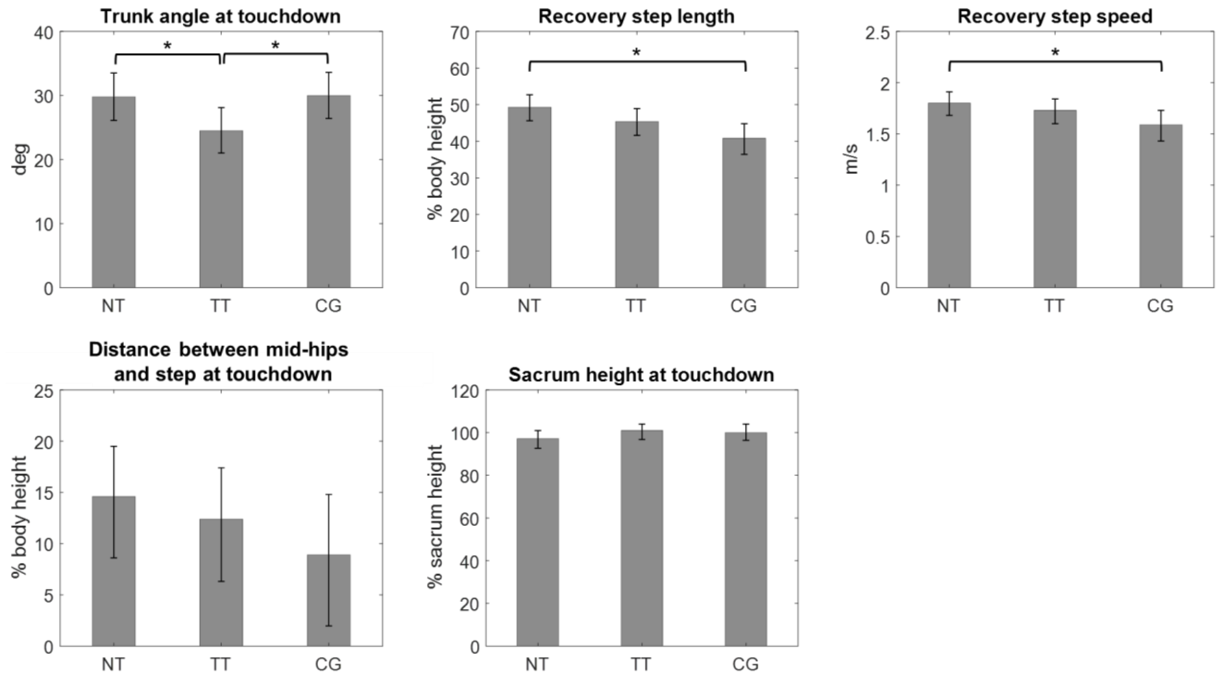

Figure 2.3. Summary of trip recovery kinematics. Each bar (error bar) represents the least squares means (95% confidence intervals of the means). Asterisk indicates statistically significant difference.

2.4. Discussion

The purpose of this study was to investigate the effects of a task-specific, non-treadmill-based trip training regimen on reactive balance among community-dwelling older adults. We first hypothesized that NT and TT participants will exhibit improved fall rates and reactive balance after laboratory-induced trips compared to CG participants. This hypothesis was supported based on the results showing that NT participants exhibited 8.5%BH longer and 0.21 m/s faster recovery step compared to CG participants, and TT participants exhibited 5.5 deg smaller trunk angle at touchdown compared to CG participants. These results suggest different beneficial effects of NT and TT in that NT might be more beneficial in improving recovery step kinematics, while TT might be more beneficial in improving trunk kinematics. We also hypothesized that TT participants will exhibit a lower fall rate and better reactive balance after laboratory-induced trips compared to NT participants. This hypothesis was also supported based on the results showing that TT participants exhibited 5.3 deg smaller trunk angle at touchdown compared to NT participants. This result further supports the beneficial effect of TT in improving trunk kinematics compared to NT.

Despite improved trip recovery kinematics among NT and TT participants, their fall rates did not differ from CG participants (Figure 2.2). It may suggest that our improvements might not have been significant enough to reduce fall rates after tripping. For example, prior studies reported that non-fallers have 7-30%BH longer recovery step (Garman et al., 2016; Grabiner et al., 2012; Marone et al., 2011; Pavol et al., 2001) and 12-39 deg smaller trunk angle (Garman et al., 2016; Grabiner et al., 2012; Marone et al., 2011; Pavol et al., 2001; P. H. Sessoms et al., 2014) compared to fallers after tripping. We saw 8.5%BH longer recovery step among only NT participants and 5.5 deg smaller trunk angle among only TT participants compared to CG participants. These improvements may not have been translated to reduction in fall rates after tripping because we saw improvements in only recovery step or trunk kinematics from our participants, and because the differences in trip recovery kinematics between fallers and non-fallers from prior studies are generally higher than the differences we saw from our NT and TT participants compared to CG participants. Unexpectedly, although not statistically significant, TT participants exhibited 13% higher fall rate than CG participants (Figure 2.2). Several reasons may explain this finding. First, individual differences (e.g., leg strength, vision, reflex) that were not measured in our study might have affected our results. Second, it was observed from video review that some of the TT participants may not have used their best effort to execute recovery steps to regain balance after tripping and were fully sustained by the fall protection harness, while they limited their trunk flexion quite well. This may have occurred because those TT participants were aware that they were wearing the harness (TT participants were likely to be more accustomed to the harness than other participants since it was provided during all TT sessions), and thus their risk of falling and injuring themselves was low.

The improved trip recovery kinematics after 3-week NT and TT generally agreed with the findings in the literature. For example, our NT participants showed 0.21 m/s faster recovery step after tripping compared to CG participants. This aligns with prior studies that showed improved reaction and movement times after 8-12 weeks of volitional step training compared to a control among older adults (Schoene et al., 2013; Shigematsu et al., 2008). Moreover, our TT participants showed 5.5 smaller trunk angle after tripping compared to CG participants. While Allin et al. (2020) reported no improvement in trunk angle after treadmill PBT over two weeks compared to a control, other studies showed 6-34 deg smaller trunk angle (Aviles et al., 2019; Bieryla et al., 2007; Grabiner et al., 2012; Oludare et al., 2018) after treadmill PBT over the time interval ranging from one day to four weeks compared to a control among older adults. A systematic review and meta-analysis by Okubo et al. (2017) reported that both volitional (similar to NT investigated here) and reactive (similar to TT investigated here) step training can reduce falls among older adults by approximately 50%. However, more studies are still needed to determine dose-response relationships for trip training and to provide better guidelines for required trip recovery kinematics that will translate to reduction in fall rates after tripping.

The different beneficial effects of NT and TT in improving trip recovery kinematics may be attributed to the difference in postural perturbations applied during each training. For example, NT involved a series of stepping exercises during which participants practiced executing a long, quick recovery step over a trip obstacle. This may have led to the improvements in both recovery step length and speed after laboratory-induced trips. NT participants also practiced arresting trunk flexion and controlling trunk posture to be vertical at touchdown of the first recovery step. However, it did not lead to the improvement in trunk angle, possibly due to self-induced perturbations that may have not been challenging enough to improve trunk control. On the other hand, TT involved exposure to larger, more sudden trip-like perturbations than NT from which participants were asked to regain balance. This may have led to the improvements in trunk angle after laboratory-induced trips like shown in other prior studies (Aviles et al., 2019; Bieryla et al., 2007; Grabiner et al., 2012; Oludare et al., 2018). Due to the limited space on the treadmill, TT participants were not encouraged to take steps as far as they could upon treadmill-induced perturbations, which may have contributed to no improvement in recovery step kinematics.

This study had several limitations that are worth mentioning. First, a group of healthy community-dwelling older adults was recruited. It is unclear how our results would generalize to other populations with different health conditions. Second, although an equal amount of training time was conducted for both NT and TT participants, there may have been differences in the number of training repetitions between groups since training was tailored to individual abilities and performances. Third, use of the fall protection harness may have caused sense of security among some participants who may not have used their best efforts to regain balance after laboratory-induced trips. Fourth, the instructions provided during outcome assessment included a warning of potential trips or slips while walking. It is not a threat to internal validity since all participants were provided with the same instructions. However, it may be a threat to external validity because such warning of potential trips or slips is not likely to be provided in the real world, and thus the responses to laboratory-induced trips may not generalize to the responses to real-world trips. Fifth, the investigators who completed the analyses were not blinded to the group allocation, which may have introduced some bias in our results.

In conclusion, our study provided evidence that there are beneficial effects of NT on improving recovery step kinematics and beneficial effects of TT on improving trunk kinematics after laboratory-induced trips among community-dwelling older adults. The difference in postural perturbations applied during training may have led to different beneficial effects between NT and TT. Further studies are needed to investigate dose-response relationships, retention of training effects over longer periods of time, and effectiveness of trip training on real-world reactive balance and falls.

References

Allin, L. J., Brolinson, P. G., Beach, B. M., Kim, S., Nussbaum, M. A., Roberto, K. A., & Madigan, M. L. (2020). Perturbation-based balance training targeting both slip-and trip-induced falls among older adults: a randomized controlled trial. *BMC geriatrics, 20*(1), 1-13.

Altman, D. G., & Bland, J. M. (2005). Treatment allocation by minimisation. *Bmj, 330*(7495), 843.

Aviles, J., Allin, L. J., Alexander, N. B., Van Mullekom, J., Nussbaum, M. A., & Madigan, M. L. (2019). Comparison of treadmill trip-like training versus tai chi to improve reactive balance among independent older adult residents of senior housing: a pilot controlled trial. *The Journals of Gerontology: Series A, 74*(9), 1497-1503.

Aviles, J., Porter, G. C., Estabrooks, P. A., Alexander, N. B., & Madigan, M. L. (2020). Potential implementation of reactive balance training within continuing care retirement communities. *Translational Journal of the American College of Sports Medicine, 5*(6), 51.

Berg, K. O., Wood-Dauphinee, S. L., Williams, J. I., & Maki, B. (1992). Measuring balance in the elderly: validation of an instrument. *Canadian journal of public health= Revue canadienne de sante publique, 83*, S7-11.

Berg, W. P., Alessio, H. M., Mills, E. M., & Tong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and Ageing, 26*(4), 261-268.

Bergen, G., Stevens, M. R., & Burns, E. R. (2016). Falls and fall injuries among adults aged≥ 65 years—United States, 2014. *Morbidity and Mortality Weekly Report, 65*(37), 993-998.

Bieryla, K. A., Madigan, M. L., & Nussbaum, M. A. (2007). Practicing recovery from a simulated trip improves recovery kinematics after an actual trip. *Gait & Posture, 26*(2), 208-213.

Centers for Disease Control and Prevention. (2017). *Leading Causes of Death Charts*. https://www.cdc.gov/injury/wisqars/LeadingCauses.html

Eng, J. J., Winter, D. A., & Patla, A. E. (1994). Strategies for recovery from a trip in early and late swing during human walking. *Experimental Brain Research, 102*, 339-349.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods, 39*(2), 175-191.

Florence, C. S., Bergen, G., Atherly, A., Burns, E., Stevens, J., & Drake, C. (2018). Medical costs of fatal and nonfatal falls in older adults. *Journal of the American Geriatrics Society, 66*(4), 693-698.

Garman, C. R., Nussbaum, M. A., Franck, C. T., & Madigan, M. L. (2016). A Pilot Study Exploring Obesity-Related Differences in Fall Rate and Kinematic Response Resulting From a Laboratory-Induced Trip. *IIE Transactions on Occupational Ergonomics and Human Factors, 4*(4), 211-221.

Gerards, M. H., McCrum, C., Mansfield, A., & Meijer, K. (2017). Perturbation-based balance training for falls reduction among older adults: Current evidence and implications for clinical practice. *Geriatrics & Gerontology International, 17*(12), 2294-2303.

Grabiner, M. D., Bareither, M. L., Gatts, S., Marone, J., & Troy, K. L. (2012). Task-specific training reduces trip-related fall risk in women.

Grabiner, M. D., Crenshaw, J. R., Hurt, C. P., Rosenblatt, N. J., & Troy, K. L. (2014). Exercise-based fall prevention: can you be a bit more specific? *Exercise and sport sciences reviews, 42*(4), 161-168.

Kaufman, K. R., Wyatt, M. P., Sessoms, P. H., & Grabiner, M. D. (2014). Task-specific Fall Prevention Training Is Effective for Warfighters With Transtibial Amputations. *Clinical Orthopaedics & Related Research, 472*(10), 3076-3084. https://doi.org/10.1007/s11999-014-3664-0

Lee, Y., Alexander, N. B., & Madigan, M. L. (2022). A proposed methodology for trip recovery training without a specialized treadmill. *Frontiers in Sports Active Living, 4*, 1003813. https://doi.org/10.3389/fspor.2022.1003813

Lurie, J. D., Zagaria, A. B., Pidgeon, D. M., Forman, J. L., & Spratt, K. F. (2013). Pilot comparative effectiveness study of surface perturbation treadmill training to prevent falls in older adults. *BMC geriatrics*, *13*(1), 49. https://doi.org/10.1186/1471-2318-13-49

Mansfield, A., Aqui, A., Centen, A., Danells, C. J., DePaul, V. G., Knorr, S., Schinkel-Ivy, A., Brooks, D., Inness, E. L., McIlroy, W. E., & Mochizuki, G. (2015, Jun 6). Perturbation training to promote safe independent mobility post-stroke: study protocol for a randomized controlled trial. *BMC Neurol, 15*, 87. https://doi.org/10.1186/s12883-015-0347-8

Mansfield, A., Schinkel-Ivy, A., Danells, C. J., Aqui, A., Aryan, R., Biasin, L., DePaul, V. G., & Inness, E. L. (2017). Does perturbation training prevent falls after discharge from stroke rehabilitation? A prospective cohort study with historical control. *Journal of Stroke and Cerebrovascular Diseases*, *26*(10), 2174-2180.

Mansfield, A., Wong, J. S., Bryce, J., Knorr, S., & Patterson, K. K. (2015). Does perturbation-based balance training prevent falls? Systematic review and meta-analysis of preliminary randomized controlled trials. *Physical Therapy, 95*(5), 700-709.

Marigold, D. S., Eng, J. J., Dawson, A. S., Inglis, J. T., Harris, J. E., & Gylfadottir, S. (2005, Mar). Exercise leads to faster postural reflexes, improved balance and mobility, and fewer falls in older persons with chronic stroke. *J Am Geriatr Soc, 53*(3), 416-423. https://doi.org/10.1111/j.1532-5415.2005.53158.x

Marone, J. R., Rosenblatt, N. J., Troy, K. L., & Grabiner, M. D. (2011, Dec). Fear of falling does not alter the kinematics of recovery from an induced trip: a preliminary study. *Arch Phys Med Rehabil*, *92*(12), 2093-2095. https://doi.org/10.1016/j.apmr.2011.06.034

Okubo, Y., Brodie, M. A., Sturnieks, D. L., Hicks, C., & Lord, S. R. (2019). A pilot study of reactive balance training using trips and slips with increasing unpredictability in young and older adults: Biomechanical mechanisms, falls and clinical feasibility. *Clinical Biomechanics, 67*, 171-179. https://doi.org/10.1016/j.clinbiomech.2019.05.016

Okubo, Y., Schoene, D., & Lord, S. R. (2017). Step training improves reaction time, gait and balance and reduces falls in older people: a systematic review and meta-analysis. *British Journal of Sports Medicine, 51*(7), 586-593.

Oludare, S. O., Pater, M. L., Rosenblatt, N. J., & Grabiner, M. D. (2018, Mar). Trip-specific training enhances recovery after large postural disturbances for which there is NO expectation. *Gait & Posture, 61*, 382-386. https://doi.org/10.1016/j.gaitpost.2018.02.001

Owings, T. M., Pavol, M. J., & Grabiner, M. D. (2001). Mechanisms of failed recovery following postural perturbations on a motorized treadmill mimic those associated with an actual forward trip. *Clinical Biomechanics, 16*(9), 813-819.

Pavol, M. J., Owings, T. M., Foley, K. T., & Grabiner, M. D. (1999). The sex and age of older adults influence the outcome of induced trips. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences, 54*(2), M103-M108.

Pavol, M. J., Owings, T. M., Foley, K. T., & Grabiner, M. D. (2001). Mechanisms Leading to a Fall From an Induced Trip in Healthy Older Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 56*(7), M428-M437.

Pigman, J., Reisman, D. S., Pohlig, R. T., Wright, T. R., & Crenshaw, J. R. (2019). The development and feasibility of treadmill-induced fall recovery training applied to individuals with chronic stroke. *BMC neurology, 19*(1). https://doi.org/10.1186/s12883-019-1320-8

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2005). Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. *Gait & Posture, 21*(4), 388-394.

Rai, S. K., Yazdany, J., Fortin, P. R., & Avina-Zubieta, J. A. (2015, Jun 3). Approaches for estimating minimal clinically important differences in systemic lupus erythematosus. *Arthritis Res Ther, 17*, 143. https://doi.org/10.1186/s13075-015-0658-6

Rosenblatt, N. J., Marone, J., & Grabiner, M. D. (2013). Preventing Trip-Related Falls by Community-Dwelling Adults: A Prospective Study. *Journal of the American Geriatrics Society, 61*(9), 1629-1631. https://doi.org/10.1111/jgs.12428

Schoene, D., Lord, S. R., Delbaere, K., Severino, C., Davies, T. A., & Smith, S. T. (2013). A randomized controlled pilot study of home-based step training in older people using videogame technology. *Plos One, 8*(3), e57734.

Sessoms, P. H., Wyatt, M., Grabiner, M., Collins, J.-D., Kingsbury, T., Thesing, N., & Kaufman, K. (2014). Method for evoking a trip-like response using a treadmill-based perturbation during locomotion. *Journal of Biomechanics, 47*(1), 277-280. https://doi.org/10.1016/j.jbiomech.2013.10.035

Sessoms, P. H., Wyatt, M., Grabiner, M., Collins, J. D., Kingsbury, T., Thesing, N., & Kaufman, K. (2014, Jan 3). Method for evoking a trip-like response using a treadmill-based perturbation during locomotion. *J Biomech, 47*(1), 277-280. https://doi.org/10.1016/j.jbiomech.2013.10.035

Shigematsu, R., Okura, T., Nakagaichi, M., Tanaka, K., Sakai, T., Kitazumi, S., & Rantanen, T. (2008). Square-Stepping Exercise and Fall Risk Factors in Older Adults: A Single-Blind, Randomized Controlled Trial. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *63*(1), 76-82. https://doi.org/10.1093/gerona/63.1.76

Shumway-Cook, A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical Therapy, 80*(9), 896-903.

Song, P. Y., Sturnieks, D. L., Davis, M. K., Lord, S. R., & Okubo, Y. (2021). Perturbation-Based Balance Training Using Repeated Trips on a Walkway vs. Belt Accelerations on a Treadmill: A Cross-Over Randomised Controlled Trial in Community-Dwelling Older Adults. *Frontiers in Sports and Active Living, 3*.

Stevens, J. A., Mahoney, J. E., & Ehrenreich, H. (2014). Circumstances and outcomes of falls among high risk community-dwelling older adults. *Injury Epidemiology, 1*(1), 5.

Sustakoski, A., Perera, S., VanSwearingen, J. M., Studenski, S. A., & Brach, J. S. (2015, Jan). The impact of testing protocol on recorded gait speed. *Gait & Posture, 41*(1), 329-331. https://doi.org/10.1016/j.gaitpost.2014.10.020

Taves, D. R. (1974). Minimization: a new method of assigning patients to treatment and control groups. *Clinical Pharmacology & Therapeutics*, *15*(5), 443-453.

UCLA Statistical Consulting Group. (2021). *ONE-WAY ANOVA POWER ANALYSIS | G*POWER DATA ANALYSIS EXAMPLES*. Retrieved April 15, 2024 from https://stats.oarc.ucla.edu/other/gpower/one-way-anova-power-analysis/

Van Dieen, J. H., Pijnappels, M., & Bobbert, M. (2005). Age-related intrinsic limitations in preventing a trip and regaining balance after a trip. *Safety science, 43*(7), 437-453.

Vellas, B. J., Wayne, S. J., Romero, L., Baumgartner, R. N., Rubenstein, L. Z., & Garry, P. J. (1997). One-leg balance is an important predictor of injurious falls in older persons. *Journal of the American Geriatrics Society, 45*(6), 735-738.

Wang, Y., Wang, S., Bolton, R., Kaur, T., & Bhatt, T. (2020). Effects of task-specific obstacle-induced trip-perturbation training: proactive and reactive adaptation to reduce fall-risk in community-dwelling older adults. *Aging clinical and experimental research, 32*(5), 893-905.

Wittich, W., Phillips, N., Nasreddine, Z. S., & Chertkow, H. (2010). Sensitivity and specificity of the Montreal Cognitive Assessment modified for individuals who are visually impaired. *Journal of visual impairment & blindness, 104*(6), 360-368.

Chapter 3. Evaluation of Inertial Measurement Units for Measuring Trunk Kinematics during Overground Trips among Community-Dwelling Older Adults

3.1. Introduction

Falls are the leading cause of non-fatal injuries across all ages in the United States (Centers for Disease Control and Prevention, 2021). Trips account for 23-32% of falls among workers (Amandus et al., 2012; Lipscomb et al., 2006) and 29-53% of falls among adults aged 65 years or older (Berg et al., 1997; Blake et al., 1988; Stevens et al., 2014). Researchers investigating balance recovery responses to laboratory-induced trips have traditionally used marker-based optical motion capture (OMC) systems (Allin et al., 2020; Crenshaw et al., 2013; Okubo et al., 2019; Pavol et al., 2001; Pijnappels et al., 2005). These systems are considered the gold standard for capturing body kinematics in biomechanics research. However, they require significant financial and space resources that can be barriers to their procurement and use. Wearable inertial measurement units (IMUs) are another type of motion capture system that can provide quantitative kinematic data with reduced cost and space needs. IMUs contain an accelerometer, gyroscope, and magnetometer, the output of which can be fused (e.g., with a Kalman filter) to provide three-dimensional orientation. Some IMUs also have a self-contained power source along with on-board data logging that eliminates the need for any other system component to be worn on the body. These features make them a viable and attractive option for motion capture inside or outside the laboratory.

To validate and facilitate IMU use for biomechanics research, prior studies have compared trunk kinematics measured with IMUs to those measured with OMC during range of motion tests assessing movement dysfunctions (Bauer et al., 2015), dynamic sports movements (Brouwer et al., 2021; Chia et al., 2021), and simulated slips/trips on a treadmill (Miller & Kaufman, 2019). The validation of IMUs to capture trunk kinematics during overground trips would build upon Miller and Kaufman (2019) and expand the suite of research tools available to trip-and-fall researchers. Moreover, four methodological alternatives could be explored. First, Miller and Kaufman (2019) placed OMC markers directly on a sternum IMU instead of more commonly used anatomical landmarks used in prior OMC studies to measure trunk kinematics during tripping (Allin et al., 2020; Crenshaw et al., 2013; Okubo et al., 2019; Pavol et al., 2001; Pijnappels et al., 2005). This precluded a direct comparison between sternum IMU-based trunk kinematic measures and often used OMC-based trunk kinematic measures. Second, Miller and Kaufman (2019) taped the sternum IMU directly to the participants' sternum while researchers or participants of future studies may prefer a chest strap harness provided by the manufacturer for easier donning and doffing. As an alternative to this chest strap harness, an IMU attached to the shoulder strap of an undergarment (e.g., bra or tank top shirt) may also be preferred by some other users. Third, capturing "sternum drop" (i.e., decrease in height for sternum over a pre-defined time interval) during trip recovery from a sternum or shoulder IMU that is already placed to capture trunk flexion angle may provide another kinematic indicator of trip recovery performance. Fourth, the ability of IMUs to capture kinematic data outside the laboratory, and their relative ease of donning and doffing, enable their extended use to capture real-world data (Handelzalts et al., 2020). However, it is necessary to investigate potential differences in IMU-based trunk kinematics when the IMU was placed on participants by experienced researchers versus by participants themselves.

The goal of this study was to investigate the concurrent validity of IMU-based trunk kinematics against OMC-based trunk kinematics after laboratory-induced overground trips while implementing the four methodological alternatives noted above. Based on the definition from Portney and Watkins (2000), concurrent validity was established if trunk kinematics from both IMU and OMC systems differed between falls and recoveries, and IMU-based trunk kinematics exhibited at least good correlation (Pearson's correlation coefficient, $r > 0.5$) with OMU-based trunk kinematics. We first hypothesized that change in trunk angle and sternum drop measured by both IMUs and OMC will differ between falls and recoveries, and exhibit at least good correlation between the two systems. We also hypothesized that change in trunk angle and sternum drop measured by a participant-placed sternum IMU will exhibit a larger variance in their errors against OMC (i.e., difference between IMU and OMC) than a researcher-placed sternum IMU. If successful, these results would support the use of IMU to capture trunk kinematics after overground trips both inside and outside the laboratory environment.

3.2. Methods

Thirty community-dwelling older adults (Figure 3.1) completed the study (12 M and 18 F; mean [SD] age: 71.8 [4.4] years; height: 1.68 [0.10] m; mass: 77.1 [16.8] kg; and unipedal stance time:17.6 [12.3] sec; five participants with one or more falls over prior six months). Participants were recruited from the university and local community via email listservs, flyers, word-of-mouth, and visits to local community organizations. Inclusion criteria required participants to be aged 65-80 years, have no lower limb amputation, weigh ≤ 250 lbs, not use a walker, not be dependent on using a cane all the time, and not regularly do any kind of exercise to improve balance (due to a related study on these same participants involving balance training). Participants were also required to pass a health screening questionnaire reviewed by a health care specialist informed of the physical requirements of the study. Exclusion criteria explicitly used in this questionnaire included: a history of hip or vertebral fracture; current back, leg, or foot pain that interfered with standing or walking; hospitalization within the last six months; score ≤ 18 on the Montreal Cognitive Assessment – Blind (Wittich et al., 2010); and osteoporosis of the lumbar spine or proximal femur as indicated by bone mineral density of *t*-score < -2.5 obtained from Dual Energy X-ray Absorptiometry (Lunar iDXA, GE Healthcare, Chicago, IL). The study was approved by the Virginia Tech Institutional Review Board, and all participants provided written consent prior to participation.

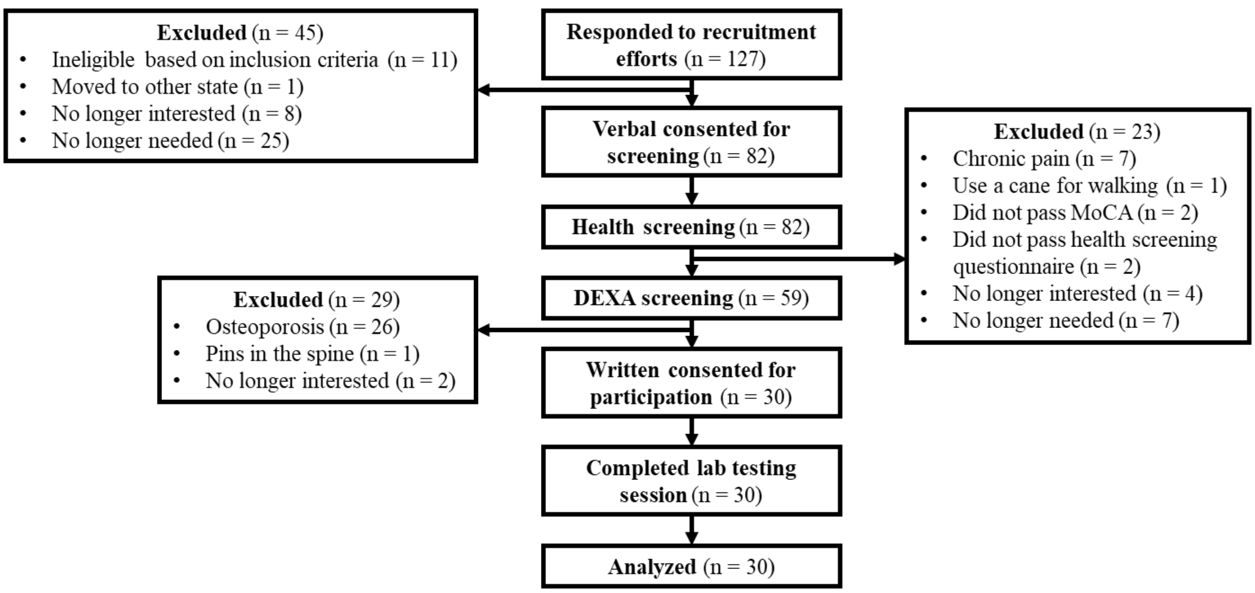

Figure 3.1. Protocol flow diagram showing participant enrollment and exclusion. MoCA = Montreal Cognitive Assessment. DEXA = Dual-Energy X-ray Absorptiometry.

Participants were asked to complete a single experimental session during which they were exposed to two laboratory-induced trips while walking on a walkway using methods reported earlier (Allin et al., 2020; Garman et al., 2016). Participants first completed a minimum of 10 walking trials on a 12-meter-long level walkway at a purposeful speed (i.e., as if they had somewhere to go) while looking straight ahead. To interject some unexpectedness with respect to the timing of the trips, participants were informed that they may or may not be exposed to one or more unexpected trips or slips while walking, and if they experience one of these, simply react naturally and continue walking. After the walking trials, a pneumatically-actuated trip obstacle integrated in the walkway was suddenly raised to a height of 8.6 cm without warning at the start of the stance phase of the non-dominant foot to attempt to trip the dominant foot during its ensuing swing phase. Afterward, attempts were made to slip participants (reported elsewhere) and trip participants once more (within two additional attempts), each after a minimum of three walking trials. Participants wore standardized footwear (New Balance Athletics, Inc.) and a safety harness attached to an overhead track along the walkway to prevent falling in the event of an unsuccessful balance recovery. The length of the harness lanyard was adjusted so that the participant's knees were approximately 10 cm from the walkway surface when asked to allow the harness to fully support their body mass and to touch their knee to the floor. To characterize participants with respect to overall fall risk, the Berg Balance Test (Berg et al., 1992) was completed before the trip trials.

Body kinematics during the trip trials were simultaneously captured using OMC and IMUs. A 13-camera OMC system (Qualisys North America, Inc., Buffalo Grove, IL) was used to sample at 128 Hz the position of 12 reflective markers (placed at acromion processes or shoulders, xiphoid process, spine at the same height as xiphoid process or back, greater trochanters or hips, tip of the second toes, lateral malleoli or ankles, and calcanei or heels), which were subsequently low-pass filtered at 10 Hz (fourth-order, zero-phase-lag, Butterworth filter). IMUs (Opal, APDM, Inc., Portland, OR) were placed on the sternum using a chest strap harness provided by the manufacturer, on the right shoulder strap of an undergarment (i.e., a tank top for males and a bra for females) using adhesive wrap, and on the dorsum of both feet, which were sampled at 128 Hz with no filter applied. The sternum IMU was donned with the chest strap harness by either the researcher or the participant, alternating between the two according to the order in which they were tested. As a part of another study on the same participants involving exploration of real-world tripping kinematics, participants were trained on how to wear sternum IMU using the chest strap harness and practiced wearing it for three weeks prior to the laboratory experimental session. Thus, no additional demonstration or training was provided for those who were asked to place the sternum IMU by themselves. Force applied to the safety harness was sampled at 1280 Hz using a uniaxial load cell (Cooper Instruments, Warrenton, VA) and subsequently low-pass filtered at 40 Hz (fourth-order, zero-phase-lag, Butterworth filter).

Data processing was performed using custom code in MATLAB R2021a (The MathWorks, Inc., Natick, MA). Our two primary outcome measures were determined during trip recovery and included *change in trunk angle* and *sternum drop*, both of which were computed using OMC and IMUs. Trunk angle was important to measure given the need to limit trunk flexion for successful trip recovery (Crenshaw et al., 2012; Grabiner et al., 2008; Pavol et al., 2001). Sternum drop was investigated because it is a function of both trunk flexion and hip drop, which must be limited for successful trip recovery (Pavol et al., 2001; Pijnappels et al., 2005). Change in trunk angle was calculated as the maximum increase in trunk flexion angle, determined using the Euler angle about a medial-lateral axis of a trunk-fixed frame, from trip onset (the time instant at which the tripped foot contacted the trip obstacle) to one second after touchdown (the time instant at which the first recover step over the trip obstacle contacted the walkway). Additional details of trip onset and touchdown are explained in Appendices Table B.1. Sternum drop was calculated as the maximum decrease in height of the sternum over the same time interval. The OMC markers attached at xiphoid process, back, and greater trochanters were used to create the trunk segment's anatomical planes and determine change in trunk angle. The OMC markers at acromion processes and xiphoid process were used to create a virtual sternum marker and determine sternum drop. IMU data from the internal accelerometer, gyroscope, and magnetometer were used with the manufacturer's proprietary Kalman filter to determine the three-dimensional orientation with respect to a fixed global frame. Calibration movements were then used with a principal component analysis to align the IMU local frame with the trunk segment's anatomical planes (Cain et al., 2016) for determining change in trunk angle. The vertical acceleration in a coordinate frame and direction that stayed aligned with gravity throughout trip recovery was integrated twice from trip onset to one second after touchdown for determining sternum drop. To minimize drift, the average vertical acceleration of IMUs when the participant was standing prior to the start of each trip trial was subtracted before the double integration.

Our secondary outcome measures included *gait speed* (anterior-posterior speed of the midpoint of the shoulder markers at trip onset), *stepping strategy* (elevating or lowering based on the definitions from Eng et al. (1994)), and *trip outcome*. Each trip outcome was classified as either a fall, recovery, harness-assist, or missed trip based on the force applied to the safety harness and video review. A fall occurred if a participant was fully and continuously supported by the harness as observed from video. A recovery occurred if an integrated harness force (i.e., an impulse from trip onset to one second after touchdown) did not exceed 20% body weight * second. A harness-assist occurred if a trial was neither a fall nor recovery. A missed trip occurred if the leading edge of the swing foot did not contact the trip obstacle during mid-to-late swing phase due to improper timing of triggering the trip obstacle.

To address our first hypothesis, a mixed-model analysis of variance (ANOVA) was used to investigate differences in our primary outcome measures of trunk kinematics between falls and recoveries for both IMUs and OMC. This analysis included additional factors of trip number, stepping strategy, gait speed, and Berg Balance Test score. We also used Pearson's correlation coefficient (r) to determine the correlation between IMU-based and OMC-based measures. This correlation was characterized as poor ($0 < r \leq 0.25$), fair ($0.25 < r \leq 0.50$), good ($0.50 < r \leq 0.75$), or strong ($r > 0.75$). To address our second hypothesis, errors in our IMU-based trunk kinematic measures against OMC-based trunk kinematic measures were first determined. Then, Levene's test was used to investigate the difference in variance of the errors between participant-placed and researcher-placed sternum IMUs. All statistical analyses were performed using JMP Pro 16 (SAS Institute, Inc., Cary, NC) with a significance level of 0.05.

3.3. Results

The 60 trip outcomes (two from each of the 30 participants) included 22 falls, 27 recoveries, 7 harness-assists, and 4 missed trips. Harness-assists, missed trips, and one fall with corrupted IMU data were excluded from further analysis. The mean (SD) gait speed across the included 48 trips was 1.53 (0.21) m/s. Regarding the first hypothesis, change in trunk angle and sternum drop measured by IMUs and OMC differed between falls and recoveries (Table 3.1) with the exception of change in trunk angle measured by the shoulder IMU (p = 0.573). Change in trunk angle exhibited good correlation with OMC when using the sternum IMU (r = 0.68) and shoulder IMU (r = 0.66). Sternum drop exhibited strong correlation with OMC when using the sternum IMU (r = 0.92) and shoulder IMU (r = 0.92) (Figure 3.2). Change in trunk angle differed between the two stepping strategies when using the sternum IMU ($p = 0.001$), shoulder IMU ($p = 0.022$), and OMC ($p < 0.001$). No differences were found in other secondary factors (see Table B.2 in Appendices for summary of the p-values).

Table 3.1. Summary of the trunk kinematic measures between falls and recoveries. Values are the least squares means (95% confidence intervals of the means). Bold indicates statistically significant.

		Fall (n = 21)	Recovery (n = 27)	*p*-value
Change in trunk angle (deg)	Sternum IMU	66.6 (57.2, 76.0)	54.4 (47.1, 61.7)	**0.026**
	Shoulder IMU	42.9 (35.3, 50.6)	45.4 (39.4, 51.3)	0.573
	OMC	38.9 (34.8, 43.0)	31.8 (28.7, 35.0)	**0.005**
Sternum drop (cm)	Sternum IMU	28.8 (23.7, 34.0)	15.0 (10.9, 19.0)	**< 0.001**
	Shoulder IMU	25.3 (20.5, 30.1)	13.1 (9.37, 16.8)	**< 0.001**
	OMC	37.6 (33.1, 42.0)	20.5 (17.0, 23.9)	**< 0.001**

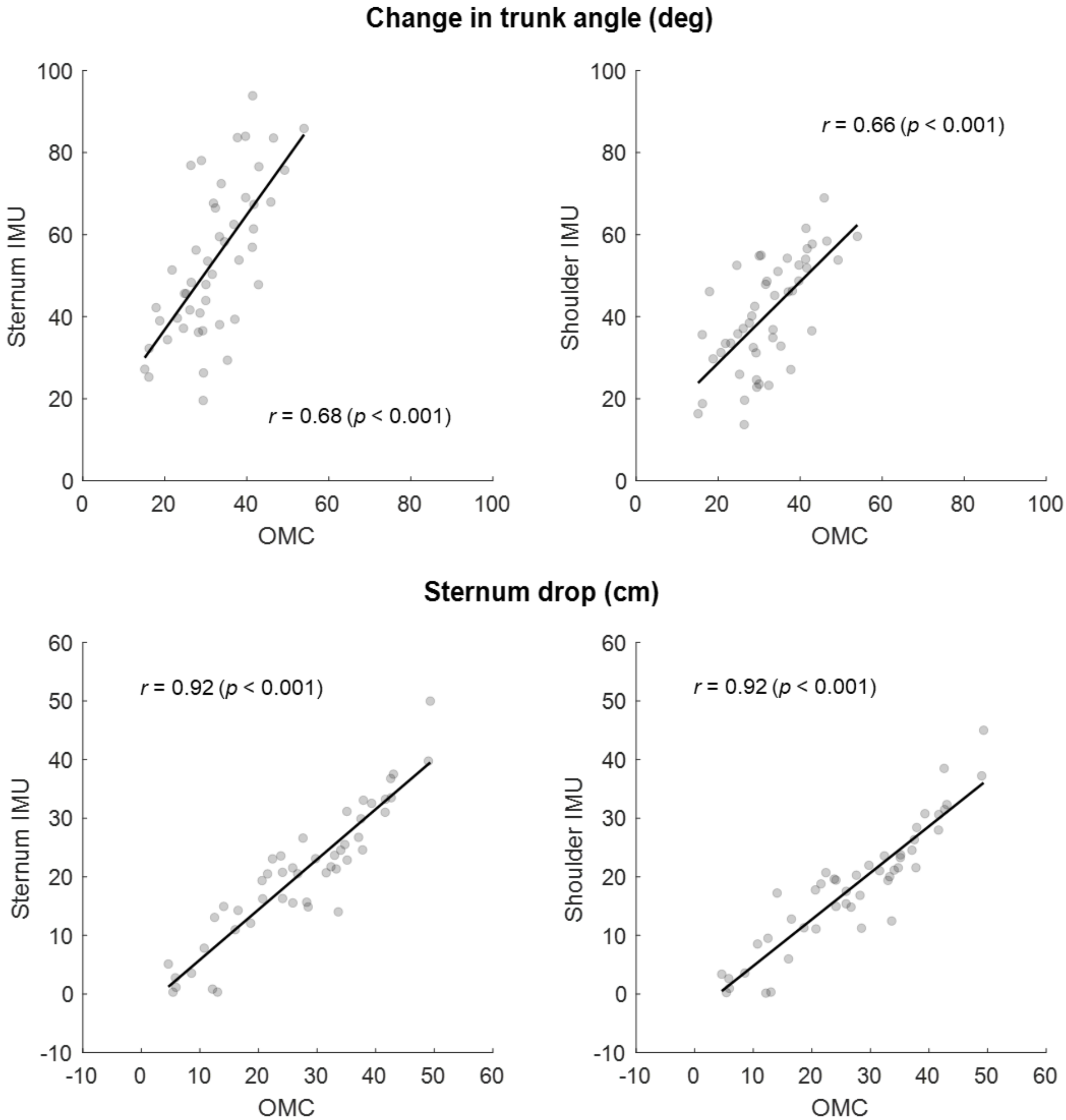

Figure 3.2. Scatterplots between IMUs and OMC. *r* = Pearson's correlation coefficient. All correlations are statistically significant. Each data point represents one trip.

Regarding the second hypothesis, the variance of the errors for change in trunk angle did not differ (p = 0.105) between researcher-placed (131.9 deg^2) and participant-placed (271.1 deg^2) sternum IMUs. Similarly, the variance of the errors for sternum drop did not differ (p = 0.795) between researcher-placed (23.2 cm^2) and participant-placed (21.2 cm^2) sternum IMUs (Figure 3.3).

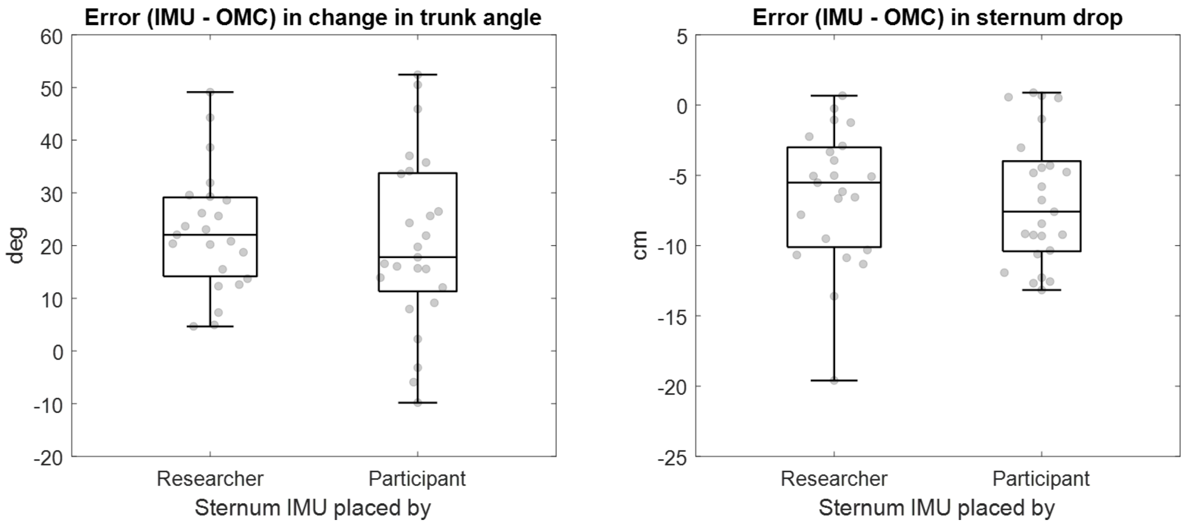

Figure 3.3. No variance difference in the errors between researcher-placed and participant-placed sternum IMUs. Each data point (gray circle) represents one trip.

3.4. Discussion

The goal of this study was to investigate the concurrent validity of IMU-based trunk kinematics against OMC-based trunk kinematics after laboratory-induced overground trips while implementing the four methodological alternatives noted above. We first hypothesized that change in trunk angle and sternum drop measured by both IMUs and OMC will differ between falls and recoveries, and exhibit at least good correlation ($r > 0.5$) between the two systems. This hypothesis was supported because the change in trunk angle and sternum drop measured by sternum IMU, shoulder IMU, and OMC differed between falls and recoveries (Table 3.1), and because IMU-based measures of change in trunk angle and sternum drop exhibited good or strong correlation with OMC-based measures (Figure 3.2). These results support the use of IMU-based trunk kinematic measures for characterizing trip recovery performance and indicate that IMU-based measures are valid predictors of the gold-standard OMC-based measures. Our results also showed differences in change in trunk angle between the stepping strategies for both IMUs and OMC. However, it is unlikely that the stepping strategy has affected the change in trunk angle as no difference was found between the trip outcome and stepping strategy (Fisher's exact test; p = 0.185).

We quantified trunk flexion angular excursion during trip recovery as the maximum increase in trunk flexion angle from trip onset to one second after touchdown of the first recovery step. We elected to use this somewhat unique approach because it is based on a relative change that would be less sensitive to bias resulting from prior relative movement of IMUs with respect to the trunk. Despite this, our mean change in trunk angle of 39 deg and 32 deg for falls and recoveries measured by OMC were comparable to prior similar studies. For example, Grabiner et al. (2012) reported the mean trunk angle of 37 deg and 22 deg at touchdown of the first recovery step for falls and recoveries among middle age and older women, and Pavol et al. (2001) reported the mean trunk angle (determined using the head-arms-torso center of mass) of 40 deg and 26 deg at touchdown of the first recovery step for falls and recoveries among community-dwelling older adults aged 65 years or older. Furthermore, Pavol et al. (2001) reported another measure of trunk flexion (i.e., trunk inclination from vertical) from trip onset to onward. This measure can be used to calculate the mean change in trunk angle (i.e., maximum increase in trunk flexion angle from trip onset to onward) that is comparable to our mean change in trunk angle, which turns out to be 48 deg and 39 deg for falls and recoveries.

The mean change in trunk angle measured by sternum and shoulder IMUs (52 deg) was higher than the mean change in trunk angle measured by OMC (35 deg). Tulipani et al. (2018) reported similar results including a 9 deg greater lumbar flexion angle from an IMU worn at L1 vertebra using an elastic band, when compared to OMC with markers placed on the trunk and lumbar spine, while participants performed functional tasks that involved bending and squatting. There are multiple reasons for these differences. First, the sternum and shoulder IMUs provide a local measure of trunk angle at the spinal level of each IMU, while the xiphoid process, back (or spine), and greater trochanter markers that are commonly used to measure trunk angle with OMC during tripping studies (Allin et al., 2020; Crenshaw et al., 2013; Okubo et al., 2019; Pavol et al., 2001; Pijnappels et al., 2005) provide more of a global measure of trunk angle. This is important because the trunk is not a rigid segment. For example, the trunk flexion that occurs upon tripping can involve a modest spinal angle (relative to vertical) in the lumbar spine and a much larger spinal angle in the thoracic spine where our sternum or shoulder IMU was worn. Second, because our participants were exposed to highly dynamic events (i.e., trips) while wearing the sternum IMU using the manufacturer-provided chest strap harness and shoulder IMU wrapped around the right shoulder strap of an undergarment, we cannot rule out relative movement between the IMUs and the trunk segment. This might have contributed to a higher change in trunk angle from IMUs than OMC with markers placed directly on the skin/body.

We also hypothesized that change in trunk angle and sternum drop measured by a participant-placed sternum IMU will exhibit a larger variance in their errors against OMC than a researcher-placed sternum IMU. This hypothesis was not supported because our results showed no variance differences in the errors for change in trunk angle and sternum drop between participant-placed and researcher-placed sternum IMUs (Figure 3.3). Similarly, Ruder et al. (2022) demonstrated the validity of gait metrics in the participant-placed IMU against the researcher-placed IMU after an alignment correction. These results suggest that community-dwelling older adults are able to don their own sternum IMU for capturing tripping kinematics outside a laboratory setting without experienced researchers. Moreover, it supports the use of a functional calibration (Cain et al., 2016) to establish a trunk-fixed coordinate aligned with the anatomical planes.

We are not aware of any other studies that have used sternum drop to characterize trip recovery kinematics. It has a theoretical basis in that it is geometrically dependent upon trunk angle and hip height, and successful trip recovery requires limiting trunk flexion and hip drop (Pavol et al., 2001; Pijnappels et al., 2005). The inability to adequately complete these requisites would increase sternum drop during trip recovery. Moreover, it is relatively insensitive to vertical position drift after double integration of vertical acceleration following gravity subtraction because it only requires such an integration over a relatively short time from trip onset to (at most) one second after touchdown of the first recovery step. We estimated this vertical drift to be less than 1 mm. Our results showed a higher correlation coefficient (r) between IMUs and OMC for sternum drop (r = 0.92) than change in trunk angle (r = 67). It may be because IMU-based sternum drop is less susceptible to relative movement of IMUs with respect to the trunk than IMU-based change in trunk angle during tripping, and thus resulted in better associations with the gold-standard OMC-based measures.

The mean sternum drop measured by sternum and shoulder IMUs (21 cm) was lower than the mean sternum drop measured by OMC (29 cm). Similar to change in trunk angle, IMUs provide a local measure of sternum drop, while OMC provide more of a global measure of sternum drop that was determined based on several markers attached to acromion processes and xiphoid process (since no marker was placed directly on the sternum). Thus, OMC-based sternum drop may have been affected by shoulder/arm movements during tripping. In addition, relative movement between the IMUs and the trunk segment might also have contributed to the difference in sternum drop between IMUs and OMC. Nevertheless, sternum drop differed between falls and recoveries for IMUs and OMC while showing strong correlation between the two systems, suggesting that it can be a useful measure of trip recovery kinematics.

This study has several limitations. First, although we used the common marker locations as other trip-related studies to determine trunk kinematics (Allin et al., 2020; Crenshaw et al., 2013; Okubo et al., 2019; Pavol et al., 2001; Pijnappels et al., 2005), not all trip-related studies used the exactly same markers, and alternative locations may affect our results. Second, we put an IMU on the right shoulder strap of an undergarment for all participants despite tripping the dominant foot of all participants (right for 45 trips and left for 3 trips). It is plausible that trunk frontal plane or transverse plane movements measured at the right shoulder after tripping could differ between trips to the contralateral or ipsilateral foot.

In conclusion, IMU-based trunk kinematics differ between falls and recoveries after laboratory-induced overground trips and correlate with the gold-standard OMC-based trunk kinematics. Therefore, they appear valid for use in capturing important trunk movement aspects of trip recovery. Also, we did not find variance differences in the errors for trunk kinematics measured by a participant-placed sternum IMU versus a researcher-placed sternum IMU. These findings expand the suite of research tools that can be used for future trip-related studies.

References

Allin, L. J., Brolinson, P. G., Beach, B. M., Kim, S., Nussbaum, M. A., Roberto, K. A., & Madigan, M. L. (2020). Perturbation-based balance training targeting both slip-and trip-induced falls among older adults: a randomized controlled trial. *BMC geriatrics*, *20*(1), 1-13.

Amandus, H., Bell, J., Tiesman, H., & Biddle, E. (2012). The epidemiology of slips, trips, and falls in a helicopter manufacturing plant. *Human factors*, *54*(3), 387-395.

Bauer, C. M., Rast, F. M., Ernst, M. J., Kool, J., Oetiker, S., Rissanen, S. M., Suni, J. H., & Kankaanpää, M. (2015). Concurrent validity and reliability of a novel wireless inertial measurement system to assess trunk movement. *Journal of Electromyography and Kinesiology*, *25*(5), 782-790.

Berg, K. O., Wood-Dauphinee, S. L., Williams, J. I., & Maki, B. (1992). Measuring balance in the elderly: validation of an instrument. *Canadian journal of public health= Revue canadienne de sante publique*, *83*, S7-11.

Berg, W. P., Alessio, H. M., Mills, E. M., & Tong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and Ageing*, *26*(4), 261-268.

Blake, A., Morgan, K., Bendall, M., Dallosso, H., Ebrahim, S., Arie, T. a., Fentem, P., & Bassey, E. (1988). Falls by elderly people at home: prevalence and associated factors. *Age and Ageing*, *17*(6), 365-372.

Brouwer, N. P., Yeung, T., Bobbert, M. F., & Besier, T. F. (2021). 3D trunk orientation measured using inertial measurement units during anatomical and dynamic sports motions. *Scandinavian Journal of Medicine & Science in Sports*, *31*(2), 358-370. https://doi.org/10.1111/sms.13851

Cain, S. M., McGinnis, R. S., Davidson, S. P., Vitali, R. V., Perkins, N. C., & McLean, S. G. (2016, Jan). Quantifying performance and effects of load carriage during a challenging balancing task using an array of wireless inertial sensors. *Gait & Posture*, *43*, 65-69.

Centers for Disease Control and Prevention. (2021). *Leading Causes of Nonfatal Injury* https://wisqars.cdc.gov/lcnf/

Chia, L., Andersen, J. T., McKay, M. J., Sullivan, J., Megalaa, T., & Pappas, E. (2021, Oct). Evaluating the validity and reliability of inertial measurement units for determining knee and trunk kinematics during athletic landing and cutting movements. *J Electromyogr Kinesiol*, *60*, 102589. https://doi.org/10.1016/j.jelekin.2021.102589

Crenshaw, J. R., Kaufman, K. R., & Grabiner, M. D. (2013). Trip recoveries of people with unilateral, transfemoral or knee disarticulation amputations: Initial findings. *Gait & Posture, 38*(3), 534-536.

Crenshaw, J. R., Rosenblatt, N. J., Hurt, C. P., & Grabiner, M. D. (2012). The discriminant capabilities of stability measures, trunk kinematics, and step kinematics in classifying successful and failed compensatory stepping responses by young adults. *Journal of Biomechanics, 45*(1), 129-133.

Eng, J. J., Winter, D. A., & Patla, A. E. (1994). Strategies for recovery from a trip in early and late swing during human walking. *Experimental Brain Research, 102*, 339-349.

Garman, C. R., Nussbaum, M. A., Franck, C. T., & Madigan, M. L. (2016). A Pilot Study Exploring Obesity-Related Differences in Fall Rate and Kinematic Response Resulting From a Laboratory-Induced Trip. *IIE Transactions on Occupational Ergonomics and Human Factors, 4*(4), 211-221.

Grabiner, M. D., Bareither, M. L., Gatts, S., Marone, J., & Troy, K. L. (2012). Task-specific training reduces trip-related fall risk in women.

Grabiner, M. D., Donovan, S., Bareither, M. L., Marone, J. R., Hamstra-Wright, K., Gatts, S., & Troy, K. L. (2008). Trunk kinematics and fall risk of older adults: translating biomechanical results to the clinic. *Journal of Electromyography and Kinesiology, 18*(2), 197-204.

Handelzalts, S., Alexander, N. B., Mastruserio, N., Nyquist, L. V., Strasburg, D. M., & Ojeda, L. V. (2020). Detection of Real-World Trips in At-Fall Risk Community Dwelling Older Adults Using Wearable Sensors. *Front Med (Lausanne), 7*, 514. https://doi.org/10.3389/fmed.2020.00514

Lipscomb, H. J., Glazner, J. E., Bondy, J., Guarini, K., & Lezotte, D. (2006). Injuries from slips and trips in construction. *Applied ergonomics, 37*(3), 267-274.

Miller, E. J., & Kaufman, K. R. (2019). Cross-sectional validation of inertial measurement units for estimating trunk flexion kinematics during treadmill disturbances. *Medical engineering & physics, 70*, 51-54.

Okubo, Y., Sturnieks, D. L., Brodie, M. A., Duran, L., & Lord, S. R. (2019, Aug 16). Effect of Reactive Balance Training Involving Repeated Slips and Trips on Balance Recovery Among Older Adults: A Blinded Randomized Controlled Trial. *J Gerontol A Biol Sci Med Sci, 74*(9), 1489-1496. https://doi.org/10.1093/gerona/glz021

Pavol, M. J., Owings, T. M., Foley, K. T., & Grabiner, M. D. (2001). Mechanisms Leading to a Fall From an Induced Trip in Healthy Older Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 56*(7), M428-M437.

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2005). Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. *Gait & Posture, 21*(4), 388-394.

Portney, L. G., & Watkins, M. P. (2000). *Foundations of Clinical Research: Applications to Practice* (2nd ed.). Prentice-Hall, Inc.

Ruder, M. C., Hunt, M. A., Charlton, J. M., Tse, C. T. F., & Kobsar, D. (2022, Sep). Original article: Validity and reliability of gait metrics derived from researcher-placed and self-placed wearable inertial sensors. *J Biomech*, *142*, 111263. https://doi.org/10.1016/j.jbiomech.2022.111263

Stevens, J. A., Mahoney, J. E., & Ehrenreich, H. (2014). Circumstances and outcomes of falls among high risk community-dwelling older adults. *Injury Epidemiology, 1*(1), 5.

Tulipani, L., Boocock, M. G., Lomond, K. V., El-Gohary, M., Reid, D. A., & Henry, S. M. (2018). Validation of an Inertial Sensor System for Physical Therapists to Quantify Movement Coordination During Functional Tasks. *Journal of applied biomechanics, 34*(1), 23-30. https://doi.org/10.1123/jab.2016-0139

Wittich, W., Phillips, N., Nasreddine, Z. S., & Chertkow, H. (2010). Sensitivity and specificity of the Montreal Cognitive Assessment modified for individuals who are visually impaired. *Journal of visual impairment & blindness*, *104*(6), 360-368.

Chapter 4. Comparison of Tripping Kinematics between the Laboratory and Real World – A Pilot Study

4.1. Introduction

Falls are the leading cause of fatal and non-fatal injuries among older adults (Bergen et al., 2016) with annual medical costs of $50 billion (Florence et al., 2018). Age-related impairments in balance and strength (Lord et al., 1994) as well as the growth of the older population (Ortman et al., 2014) contribute to the prevalence of these falls and injuries. Falls can occur due to various reasons, among which trips account for 29-53% falls in community-dwelling older adults (Berg et al., 1997; Blake et al., 1988; Stevens et al., 2014).

Numerous laboratory studies have induced trips among older adults to identify factors affecting trip recovery (Garman et al., 2015; Pater et al., 2016; Rosenblatt & Madigan, 2021), explore the biomechanical mechanisms underlying trip-induced falls (Pavol et al., 2001; Pijnappels et al., 2005; Van Dieen et al., 2005), and evaluate the efficacy of interventions aiming to reduce the prevalence of trip-induced falls (Aviles et al., 2019; Bieryla et al., 2007; Grabiner et al., 2012; Song et al., 2021; Wang et al., 2020). While these studies have led to a wealth of knowledge, how well these laboratory findings generalize to real-world trips outside the laboratory setting and during normal daily life remains unclear. Along with our Study 2 (Chapter 3), two prior studies have demonstrated the feasibility of using inertial measurement units (IMUs) and a voice recorder to capture real-world tripping kinematics and their context among community-dwelling older adults (Handelzalts et al., 2020; Ojeda et al., 2019). A similar approach could be used to investigate the association between the laboratory and real-world trips.

The goal of this pilot study was to explore differences in tripping kinematics between the laboratory and real world. We hypothesized that tripping kinematics will exhibit a higher variance in the real world than in the laboratory. This was based upon the expectation that real-world tripping scenarios would be more varied and diverse than those in a controlled laboratory study. For example, environmental factors (e.g., ground/floor/trip obstacle material properties and geometry) and behavioral factors (e.g., gait speed, dual-task participation, attention, and awareness) are expected to vary more in the real world than in a laboratory study and thus result in greater variance in tripping kinematics. The results of this pilot study may facilitate future studies that 1) determine how laboratory studies of tripping risk factors and biomechanical mechanisms generalize to the real world, 2) attempt to mimic real-world tripping scenarios in the laboratory, and 3) investigate how balance training interventions transfer to the real world.

4.2. Methods

Twenty community-dwelling older adults (8 M and 12 F) from a larger study investigating the effects of perturbation-based balance training (PBT) on laboratory tripping kinematics (see Chapter 2) were included for this study. These 20 participants were chosen because they were allocated to either an established PBT intervention (Allin et al., 2020; Grabiner et al., 2012) or a control group receiving no intervention. Participants had a mean (SD) age of 71.8 (4.6) years, body height of 1.70 (0.11) m, body mass of 80.8 (15.9) kg, and unipedal stance time of 16.9 (12.9) sec, and four participants reported one or more falls over prior six months. Inclusion criteria required participants to be aged 65-80 years, have no lower limb amputation, weigh ≤ 250 lbs, not use a walker, not be dependent on using a cane all the time, and not regularly do any kind of exercise to improve balance. Participants were also required to pass a health screening questionnaire reviewed by a health care specialist informed of the physical requirements of the study. Exclusion criteria explicitly used in this questionnaire included: a history of hip or vertebral fracture; current back, leg, or foot pain that interfered with standing or walking; hospitalization within the last six months; score $\leq$ 18 on the Montreal Cognitive Assessment – Blind (Wittich et al., 2010); and osteoporosis of the lumbar spine or proximal femur as indicated by bone mineral density of *t*-score < -2.5 obtained from Dual Energy X-ray Absorptiometry (Lunar iDXA, GE Healthcare, Chicago, IL). Participants were recruited from the university and local community via email listservs, flyers, word-of-mouth, and visits to local community organizations. Recruitment started in October 2022, and all training and testing were completed in August 2023. The study was approved by the Virginia Tech Institutional Review Board, and all participants provided written consent prior to participation.

A repeated-measures experimental design was used. Although not the primary focus here, participants first completed either three weeks of twice weekly PBT or no intervention (i.e., control group). Afterward, and of the primary focus here, participants wore three IMUs and a wrist-worn voice recorder daily for three weeks to capture real-world loss of balance (LOB) kinematics and context. Participants then completed a single testing session during which they were exposed to two laboratory-induced trips while wearing the same three IMUs.

Participants reported to the laboratory to receive the devices, a demonstration of their usage, and a study instruction manual developed by the investigators. Participants were asked to don the IMUs (Opal, APDM, Inc., Portland, OR) and voice recorder (BestRec, 16GB Digital Voice Recorder) each day when they were ready to start their daily activities in the morning, wear the devices throughout the day (other than while bathing or participating in activities during which they could get wet), and remove the devices when they finished their daily activities in the evening. This schedule was chosen because IMU battery life was approximately 12 hours and required overnight charging. The times the devices were worn by participants ranged from 6 am to 10 pm based on participant preference. One IMU was worn on sternum using the manufacturer's chest strap harness, and the other two were worn on the dorsum of the feet using the laboratory-provided shoe pouches that were secured to the shoelaces. Body kinematics were sampled at 128 Hz and continuously logged onboard the IMUs from the moment they were unplugged from the charger in the morning to the moment they were plugged back into the charger in the evening (or until the battery was fully drained). The voice recorder was worn on the wrist and used to document the context of any real-world LOB immediately it was experienced or as soon after as possible. Details of the information requested in the voice recordings are reported elsewhere (Lee et al., 2024). Voice recordings also provided a time stamp of the LOB that aided in finding LOBs within IMU data. After participants' first visit, investigators contacted participants via phone call or text at least once during each of the three weeks to address any questions or issues. Participants also visited our laboratory toward the end of the first and second weeks for investigators to download all data from the devices and to address any questions or issues.

After the three-weeks of real-world LOB capture, participants completed a single testing session during which they were exposed to two laboratory-induced trips while walking overground using methods described elsewhere (Allin et al., 2020; Garman et al., 2016). Briefly, participants wore the same three IMUs that they wore during the real-world LOB capture and were asked to complete multiple walking trials on a 12-meter level walkway at a purposeful speed (i.e., as if they were going somewhere) while looking straight ahead. To interject some unexpectedness with respect to the timing of the trips, they were informed that some participants may be exposed to one or more unexpected trips or slips while walking, and to simply react naturally and continue walking if they experience one of them. After completing a minimum of 10 walking trials, a trip obstacle integrated into the walkway was abruptly raised to a height of 8.6 cm without warning at the start of the stance phase of the non-dominant foot to induce a trip to the dominant foot during its ensuing swing phase. Afterward, attempts were made to slip participants (reported elsewhere) and trip participants once more (within two additional attempts), each after a minimum of three walking trials. Participants wore standardized footwear (New Balance Athletics, Inc.) and a full body fall protection harness for their safety in the event of an unsuccessful balance recovery. Force applied to the fall protection harness was sampled at 1280 Hz using a uniaxial load cell (Cooper Instruments, Warrenton, VA) and low-pass filtered at 40 Hz (fourth-order, zero-phase-lag, Butterworth filter). Each trip outcome was classified as either a fall, recovery, harness-assist, or missed trip based on the force applied to the fall protection harness and video review. A fall occurred if a participant was fully and continuously supported by the harness as observed from video. A recovery occurred if an integrated harness force (i.e., an impulse from trip onset to one second after touchdown) did not exceed 20% body weight * second. A harness-assist occurred if a trial was neither a fall nor recovery. A missed trip occurred if the leading edge of the swing foot did not contact the trip obstacle during mid-to-late swing phase, due to improper timing of triggering the trip obstacle. Subsequent data processing was performed using custom code in MATLAB R2021a (The MathWorks Inc., Natick, MA).

During the three-weeks of real-world LOB capture, participants used the voice recorder to document their responses to six questions regarding the context of each LOB they experienced (see Table C.1 in Appendices). A LOB was defined as “a sudden, unexpected, and unintended change in body position that requires us to do something to regain our balance or else we will fall.” LOBs were identified within the IMU data using the time stamps of the voice recordings. A total of 153 LOBs were reported from 18 of the 20 participants (two participants did not report any LOB). These LOBs were then screened to limit subsequent analyses to those that were described as a trip or trip-like perturbations (e.g., “caught foot on”, “stubbed foot”) and have IMU data correspond to such descriptions (Handelzalts et al., 2020), both of which were comparable in their overall context to the laboratory-induced trips. This resulted in 24 real-world trips from 14 participants who were walking forward (not on stairs) without carrying anything, received no external support, and showed identifiable tripping kinematics from all three IMUs (Figure 4.1). The transcribed voice recordings for these 24 real-world trips are included in Appendices Table C.2.

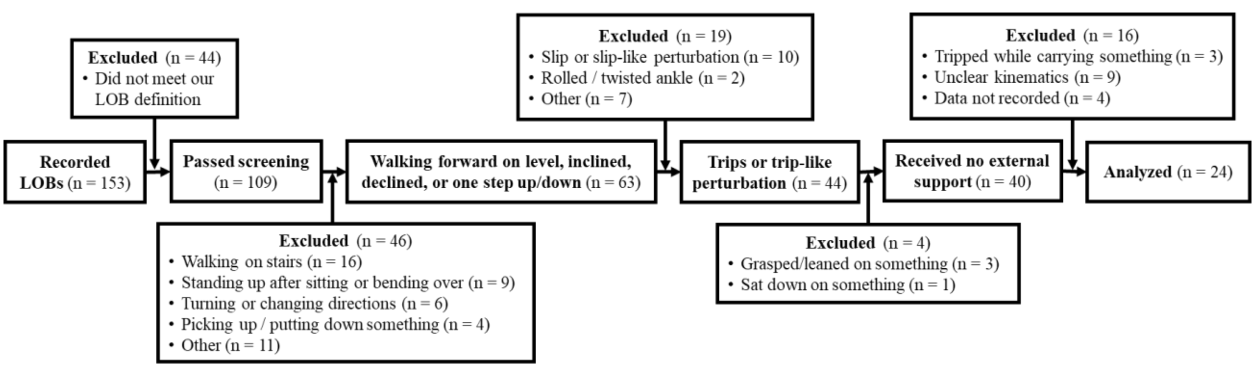

Figure 4.1. Flow diagram showing screening processes for the reported LOBs.

Our two primary outcome measures were *change in trunk angle* and *sternum drop*. Data from the sternum IMU's internal accelerometer, gyroscope, and magnetometer was used with the manufacturer's proprietary Kalman filter to determine its three-dimensional orientation with respect to a fixed global frame. Calibration movements were then used with a principal component analysis to align the IMU local frame with the anatomical planes (Cain et al., 2016). The Euler angle with respect to the medial-lateral axis was computed as trunk angle and expressed relative to standing posture. Change in trunk angle was the maximum increase in trunk flexion angle from trip onset (the time instant at which the tripped foot contacted the trip obstacle as determined by the resultant acceleration of the foot IMU) to one second after touchdown (the time instant at which the first recovery step over the trip obstacle contacted the walkway as determined by the resultant acceleration of the foot IMU). Change in trunk angle was selected based upon the importance of limiting trunk flexion for successful trip recovery (Crenshaw et al., 2012; Grabiner et al., 2008; Pavol et al., 2001) and because data analysis indicated the trunk angle at trip onset was not as consistently upright during real-world LOBs as in laboratory tripping studies. To determine sternum drop, the vertical acceleration of the sternum IMU in a coordinate frame and direction that stayed aligned with gravity throughout trip recovery was integrated twice from trip onset to one second after touchdown. To minimize drift, the average vertical acceleration of this IMU when the participant was stationary prior to the start of each real-world or laboratory-induced trip was subtracted before the double integration. Sternum drop was the maximum decrease in height of the sternum IMU from trip onset to one second after touchdown. Sternum drop was investigated because it may be sensitive to both trunk flexion and hip drop, both of which must be limited for successful trip recovery (Pavol et al., 2001; Pijnappels et al., 2005).

Levene's test was used to investigate differences in the variance of tripping kinematics between the real-world and laboratory-induced trips. Because all real-world trips resulted in a successful balance recovery (i.e., no falls were reported in the voice recordings), only laboratory-induced trips that resulted in a recovery were included in the Levene's test to avoid biasing the comparison from other trips that did not result in a recovery. Statistical analyses were performed using JMP Pro 16 (SAS Institute, Inc., Cary, NC) with a significance level of 0.05.

4.3. Results

Among the 14 participants who reported 24 real-world trips, seven PBT participants reported 10 real-world trips, while seven control participants reported 14 real-world trips (Figure 4.2). A total of 28 laboratory-induced trips (two per the 14 participants) resulted in 12 recoveries. Across real-world and laboratory-induced trips, change in trunk angle exhibited a median (range) of 19.5 (2.07 – 85.9) deg, while sternum drop exhibited a median (range) of 4.95 (0 – 23.1) cm (Figure 4.3). The variance of change in trunk angle was lower (p = 0.049) for the real-world trips (155 deg^2) than laboratory-induced trips (365 deg^2), while the variance of sternum drop was not different (p = 0.422) between the real-world trips (47.9 cm^2) and laboratory-induced trips (64.8 cm^2). The mean change in trunk angle was 14.5 deg for the real-world trips and 50.5 deg for the laboratory-induced trips, while the mean sternum drop was 5.92 cm for the real-world trips and 11.3 cm for the laboratory-induced trips. The variance of change in trunk angle across the real-world and laboratory-induced trips was not different (p = 0.449) between the PBT (601 deg^2) and control (463 deg^2) groups, while the variance of sternum drop across the real-world and laboratory-induced trips was also not different (p = 0.511) between the PBT (65.1 cm^2) and control (49.1 cm^2) groups (Figure 4.4).

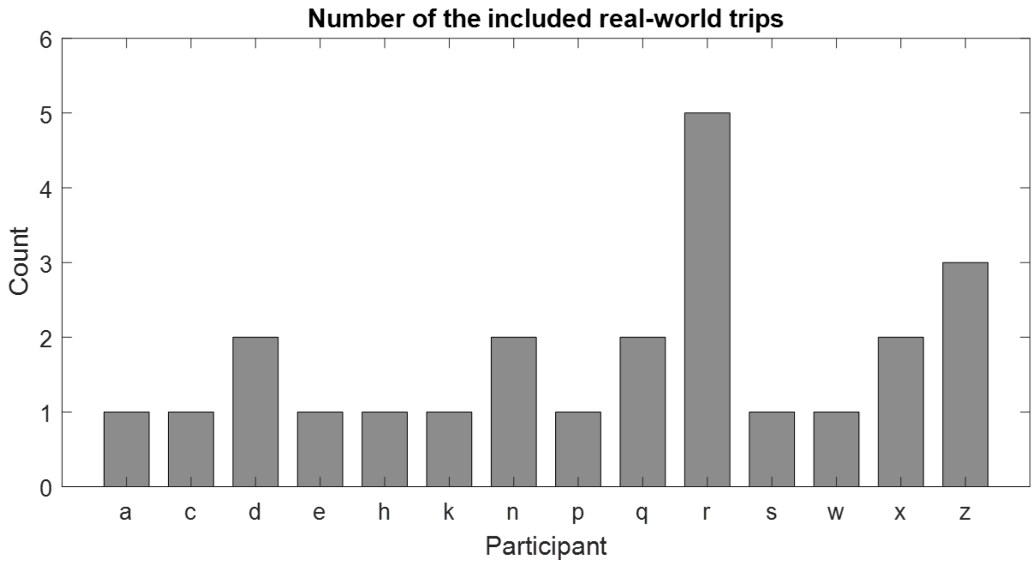

Figure 4.2. Distribution of real-world trips reported by each participant. The alphabetical letters represent different participants. PBT participants = e, h, n, q, s, w, and x. Control participants = a, c, d, k, p, r, and z.

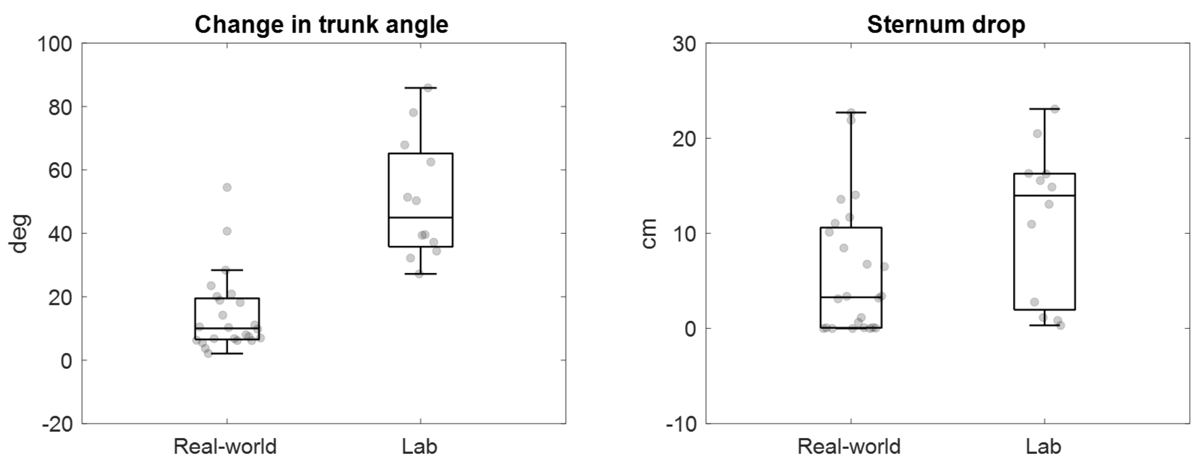

Figure 4.3. Lower variance in change in trunk angle among the real-world trips than laboratory-induced trips. No variance difference in sternum drop between the real-world and laboratory-induced trips. Each data point represents one trip.

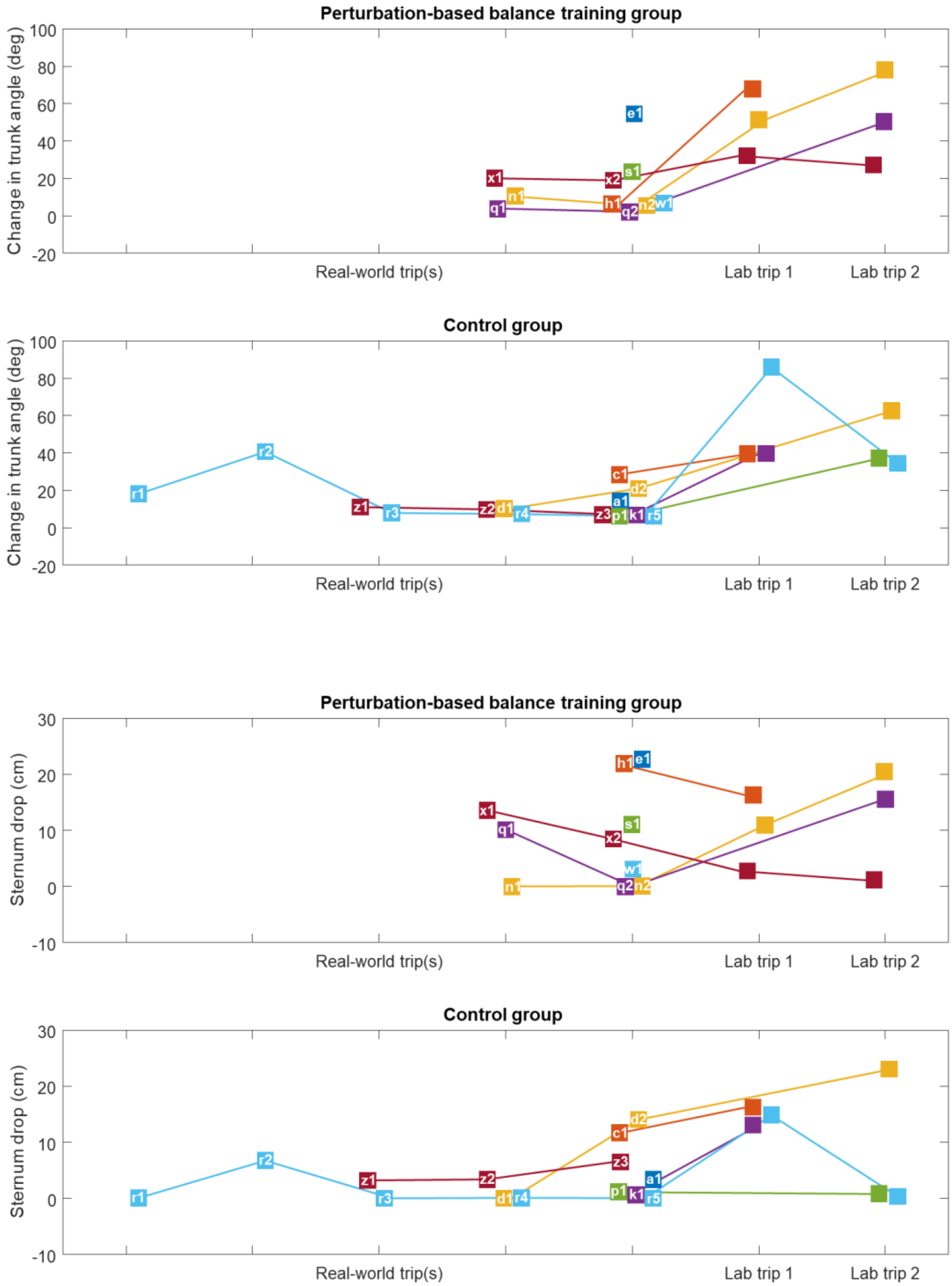

Figure 4.4. Change in trunk angle and sternum drop of the real-world and laboratory-induced trips that resulted in a recovery. Each participant is assigned an alphabetical letter and number(s) for the real-world trips (see Table C.2 in Appendices for their transcribed voice recordings). Separate plots were created for the PBT and control participants for clarity in showing no variance differences between the two groups.

4.4. Discussion

The goal of this pilot study was to explore differences in tripping kinematics between the laboratory and real world. We hypothesized that tripping kinematics will exhibit a higher variance in the real world than in the laboratory. Interestingly, the opposite was the case in that variance in change in trunk angle was 210 deg^2 lower among the real-world trips than the laboratory-induced trips. There are multiple possible reasons for this. First, the height of the trip obstacle used in the laboratory was 8.6 cm. Most real-world trip obstacles might not be as high and thus less difficult for recovery. Less difficult trips could lead to less variability in tripping kinematics because balance recovery is less challenging. For example, many of the real-world trips used in our analysis were scuffs (see Table C.2 in Appendices), which occur during swing phase of the gait cycle when the forward motion of the swing foot is impeded by some friction between the ground/floor and the bottom of shoes. This type of trip-like perturbation is a minor LOB and may have not altered tripping kinematics as much as the laboratory-induced trips where participants were tripped by a rigid obstacle. Our results showing the mean change in trunk angle of 14.5 deg for the real-world trips and 50.5 deg for the laboratory-induced trips support the explanation of the lower severity in the real-world trips compared to the laboratory-induced trips. Second, the walking speed in the laboratory may have been faster than the walking speed in some of the real-world trips. Participants were asked to walk at a purposeful speed (i.e., as if they were going somewhere) for the laboratory-induced trips as a part of the larger study investigating the effects of PBT on laboratory tripping kinematics. Although we have no measure of gait speed in the real world, it is likely that the gait speed was slower as participants walked at a more comfortable pace than in the laboratory, and because some real-world trips occurred near gait initiation when the speed was likely slower (see

Table C.2 in Appendices). This may have resulted in lower trip severity in the real world and thus contributed to lower variance in tripping kinematics compared to the laboratory-induced trips.

Our mean change in trunk angle from the laboratory-induced trips was generally comparable to those from prior similar studies. Pavol et al. (2001) used a 5.1 cm high trip obstacle and instructed participants to walk at a self-selected normal speed. They reported the mean maximum trunk angle from vertical (determined from trip onset to onward) of 47.5 deg for recoveries among community-dwelling older adults aged 65 years or older. Bieryla et al. (2007) used a 7.6 cm high trip obstacle and instructed participants to walk at a self-selected normal speed. They reported the mean maximum trunk angle (determined over the first two recovery steps) of approximately 41 deg for one fall and 10 recoveries among community-dwelling older adults aged 63-83 years old. We used an 8.6 cm high trip obstacle and instructed participants to walk at a purposeful walking speed. Our results showed the mean change in trunk angle of 50.5 deg for recoveries among community-dwelling older adults aged 65-80 years old. Although the reported maximum trunk angles from these two prior studies were a global measure of trunk angle based on several markers attached to the trunk segment, they appear comparable to our change in trunk angle measured from sternum IMU that was a local measure of trunk angle during trip recovery.

Many prior studies showed the effects of PBT in improving reactive balance after laboratory-induced trips (Grabiner et al., 2012; Song et al., 2021; Wang et al., 2020). Based on such findings in the literature, we generally expected improved tripping kinematics from the PBT participants than the control participants both in the laboratory and real world. However, no clear differences in change in trunk angle and sternum drop were visible between the PBT and control participants

(Figure 4.4). Our results also showed no variance differences in the change in trunk angle and sternum drop between the PBT and control participants across the real-world and laboratory-induced trips. This may have been attributed to baseline individual differences (e.g., leg strength, vision, reaction time) that were not measured as a part of the PBT study. In addition, the included real-world trips may have not been challenging enough (or the laboratory-induced trips may have been too challenging) to show differences between the PBT and control participants. Further studies are necessary to determine the required dosage of PBT that may result in optimal outcomes.

Sternum height is a function of trunk angle and hip height. Successful trip recovery requires limiting trunk flexion and hip drop (Pavol et al., 2001; Pijnappels et al., 2005). As such, sternum drop during trip recovery would seem to be an indicator of trip recovery performance with an increase in trunk flexion and hip drop indicating poorer performance. A prior study (Chapter 3) showed that sternum drop is larger during falls than recoveries after a laboratory-induced trip. Moreover, sternum drop is amenable to IMU capture because it depends on a relative change from trip onset to (at most) one second after touchdown of the first recovery step (as used here) and not on absolute values of sternum height above the ground level that can be more susceptible to drift.

Our study has several limitations that should be discussed. First, the real-world LOBs captured here may have been influenced by the Hawthorne effect (i.e., change in behavior among participants as being evaluated in a research study) and thus not as ecologically valid as individuals not in a research study. Second, a group of healthy community-dwelling older adults was recruited. It is unclear how our results would generalize to other populations with different health conditions. Third, to capture real-world LOB kinematics, participants were asked to wear the IMUs and voice recorder for three weeks during different seasons of the year. The frequency and/or context of real-world LOBs may have been different if participants were asked to wear the devices for a longer period and/or during different environmental conditions. Fourth, the laboratory-induced trips involved wearing a full body fall protection harness, while the real-world trips did not. Wearing the harness may have caused sense of security among some participants who may not have used their best efforts to regain balance after the laboratory-induced trips, and thus contributed to higher variance in tripping kinematics compared to the real-world trips. Fifth, we have a limited number of outcome measures that focus on trunk kinematics after tripping and did not include other known important trip recovery measures, such as (change in) trunk angular velocity and stepping-related measures. Change in trunk angle and sternum drop were chosen because they are less sensitive to artifacts that may be created by relative movements of IMUs with respect to the trunk than trunk angular velocity, and because it is very difficult and challenging to accurately estimate the relative distance from one IMU to another IMU for calculating stepping kinematics during tripping.

In conclusion, this is the first study to explore differences in tripping kinematics between the laboratory and real world among community-dwelling older adults. Our study showed the feasibility of using IMUs and voice recorder to understand the underlying mechanisms and context of real-world LOBs. It may enable investigating the effects of PBT outside the laboratory settings in future studies.

References

Allin, L. J., Brolinson, P. G., Beach, B. M., Kim, S., Nussbaum, M. A., Roberto, K. A., & Madigan, M. L. (2020). Perturbation-based balance training targeting both slip-and trip-induced falls among older adults: a randomized controlled trial. *BMC geriatrics, 20*(1), 1-13.

Aviles, J., Allin, L. J., Alexander, N. B., Van Mullekom, J., Nussbaum, M. A., & Madigan, M. L. (2019). Comparison of treadmill trip-like training versus tai chi to improve reactive balance among independent older adult residents of senior housing: a pilot controlled trial. *The Journals of Gerontology: Series A, 74*(9), 1497-1503.

Berg, W. P., Alessio, H. M., Mills, E. M., & Tong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and Ageing, 26*(4), 261-268.

Bergen, G., Stevens, M. R., & Burns, E. R. (2016). Falls and fall injuries among adults aged≥ 65 years—United States, 2014. *Morbidity and Mortality Weekly Report, 65*(37), 993-998.

Bieryla, K. A., Madigan, M. L., & Nussbaum, M. A. (2007). Practicing recovery from a simulated trip improves recovery kinematics after an actual trip. *Gait & Posture, 26*(2), 208-213.

Blake, A., Morgan, K., Bendall, M., Dallosso, H., Ebrahim, S., Arie, T. a., Fentem, P., & Bassey, E. (1988). Falls by elderly people at home: prevalence and associated factors. *Age and Ageing, 17*(6), 365-372.

Cain, S. M., McGinnis, R. S., Davidson, S. P., Vitali, R. V., Perkins, N. C., & McLean, S. G. (2016, Jan). Quantifying performance and effects of load carriage during a challenging balancing task using an array of wireless inertial sensors. *Gait & Posture, 43*, 65-69.

Crenshaw, J. R., Rosenblatt, N. J., Hurt, C. P., & Grabiner, M. D. (2012). The discriminant capabilities of stability measures, trunk kinematics, and step kinematics in classifying successful and failed compensatory stepping responses by young adults. *Journal of Biomechanics, 45*(1), 129-133.

Florence, C. S., Bergen, G., Atherly, A., Burns, E., Stevens, J., & Drake, C. (2018). Medical costs of fatal and nonfatal falls in older adults. *Journal of the American Geriatrics Society, 66*(4), 693-698.

Garman, C. R., Franck, C. T., Nussbaum, M. A., & Madigan, M. L. (2015). A bootstrapping method to assess the influence of age, obesity, gender, and gait speed on probability of tripping as a function of obstacle height. *Journal of Biomechanics, 48*(6), 1229-1232.

Garman, C. R., Nussbaum, M. A., Franck, C. T., & Madigan, M. L. (2016). A Pilot Study Exploring Obesity-Related Differences in Fall Rate and Kinematic Response Resulting From a Laboratory-Induced Trip. *IIE Transactions on Occupational Ergonomics and Human Factors, 4*(4), 211-221.

Grabiner, M. D., Bareither, M. L., Gatts, S., Marone, J., & Troy, K. L. (2012). Task-specific training reduces trip-related fall risk in women.

Grabiner, M. D., Donovan, S., Bareither, M. L., Marone, J. R., Hamstra-Wright, K., Gatts, S., & Troy, K. L. (2008). Trunk kinematics and fall risk of older adults: translating biomechanical results to the clinic. *Journal of Electromyography and Kinesiology, 18*(2), 197-204.

Handelzalts, S., Alexander, N. B., Mastruserio, N., Nyquist, L. V., Strasburg, D. M., & Ojeda, L. V. (2020). Detection of Real-World Trips in At-Fall Risk Community Dwelling Older Adults Using Wearable Sensors. *Front Med (Lausanne), 7*, 514. https://doi.org/10.3389/fmed.2020.00514

Lee, Y., Nyquist, L., Alexander, N. B., & Madigan, M. L. (2024). Using Voice Recorders to Document Losses of Balance and Their Context during the Daily Lives of Community-Dwelling Older Adults. Abstract submitted for review. Annual Meeting of American Society of Biomechanics, Madison, WI, USA.

Lord, S. R., Ward, J. A., Williams, P., & Anstey, K. J. (1994). Physiological factors associated with falls in older community-dwelling women. *Journal of the American Geriatrics Society, 42*(10), 1110-1117.

Ojeda, L. V., Adamczyk, P. G., Rebula, J. R., Nyquist, L. V., Strasburg, D. M., & Alexander, N. B. (2019, Feb). Reconstruction of body motion during self-reported losses of balance in community-dwelling older adults. *Med Eng Phys, 64*, 86-92. https://doi.org/10.1016/j.medengphy.2018.12.008

Ortman, J. M., Velkoff, V. A., & Hogan, H. (2014). An aging nation: the older population in the United States.

Pater, M. L., Rosenblatt, N. J., & Grabiner, M. D. (2016, May 3). Knee osteoarthritis negatively affects the recovery step following large forward-directed postural perturbations. *J Biomech, 49*(7), 1128-1133. https://doi.org/10.1016/j.jbiomech.2016.02.048

Pavol, M. J., Owings, T. M., Foley, K. T., & Grabiner, M. D. (2001). Mechanisms Leading to a Fall From an Induced Trip in Healthy Older Adults. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 56*(7), M428-M437.

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2005). Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. *Gait & Posture, 21*(4), 388-394.

Rosenblatt, N. J., & Madigan, M. L. (2021). Exploring the association between measures of obesity and measures of trip-induced fall risk among older adults. *Archives of Physical Medicine and Rehabilitation*.

Song, P. Y., Sturnieks, D. L., Davis, M. K., Lord, S. R., & Okubo, Y. (2021). Perturbation-Based Balance Training Using Repeated Trips on a Walkway vs. Belt Accelerations on a

Treadmill: A Cross-Over Randomised Controlled Trial in Community-Dwelling Older Adults. *Frontiers in Sports and Active Living*, *3*.

Stevens, J. A., Mahoney, J. E., & Ehrenreich, H. (2014). Circumstances and outcomes of falls among high risk community-dwelling older adults. *Injury Epidemiology*, *1*(1), 5.

Van Dieen, J. H., Pijnappels, M., & Bobbert, M. (2005). Age-related intrinsic limitations in preventing a trip and regaining balance after a trip. *Safety science, 43*(7), 437-453.

Wang, Y., Wang, S., Bolton, R., Kaur, T., & Bhatt, T. (2020). Effects of task-specific obstacle-induced trip-perturbation training: proactive and reactive adaptation to reduce fall-risk in community-dwelling older adults. *Aging clinical and experimental research, 32*(5), 893-905.

Wittich, W., Phillips, N., Nasreddine, Z. S., & Chertkow, H. (2010). Sensitivity and specificity of the Montreal Cognitive Assessment modified for individuals who are visually impaired. *Journal of visual impairment & blindness*, *104*(6), 360-368.

Chapter 5. Conclusion

5.1. Summary

Trip-induced falls among older adults remain a major public health problem despite mitigation efforts. Three studies were designed to (1) improve the feasibility and accessibility of trip training, (2) expand the trip-related research scope outside a laboratory setting, and (3) explore tripping kinematics in the real world.

The first study (Chapter 2) investigated the effects of a task-specific, non-treadmill-based trip training regimen on reactive balance after laboratory-induced trips among community-dwelling older adults. Separate groups of participants completed novel non-treadmill training (NT), commonly used treadmill-training (TT), and no training as a control for three weeks. Our results showed different beneficial effects of the two trip training regimens. NT may be more beneficial in improving recovery step kinematics, because of its specific instructions on taking a long, quick recovery step over a trip obstacle, while TT may be more beneficial in improving trunk kinematics, because of repeated exposure to larger, more sudden trip-like perturbations than NT during which participants were encouraged to regain balance.

The second study (Chapter 3) investigated the concurrent validity of inertial measurement unit (IMU)-based trunk kinematics against the gold-standard optical motion capture (OMC)-based trunk kinematics during laboratory-induced overground trips among community-dwelling older adults. IMUs placed on sternum and shoulder, as well as OMC markers attached at anatomical landmarks of the trunk segment, were used to capture trunk kinematics during two laboratory-induced trips. Our results showed that IMU-based trunk kinematics differed between falls and recoveries after tripping, and exhibited at least good correlation ($r > 0.5$) with the gold-standard OMC-based trunk kinematics. In addition, the variance in the errors for IMU-based trunk kinematics did not differ when IMU was placed by researcher versus participant. This suggests that community-dwelling older adults are able to don their own sternum IMU for capturing tripping kinematics outside a laboratory setting, expanding the suite of research tools that can be used for future trip-related studies.

The third study (Chapter 4) explored the differences in tripping kinematics between the laboratory and real world among community-dwelling older adults. Participants were asked to wear IMUs and a voice recorder during daily life for three weeks to capture their kinematic responses during real-world trips. This study demonstrated the feasibility of using IMUs and a voice recorder to understand the underlying mechanisms and context of real-world trips. It also provided pilot data for planning a future trial to investigate effects of trip training in the real world.

5.2. Future Work

Several future studies can be planned based on the findings from the three studies reported here. The first study (Chapter 2) exhibited improved trip recovery kinematics after NT and TT, but these improvements did not translate to reduction in fall rates after laboratory-induced trips. Future studies are necessary to determine dose-response relationship and retention of training effects that may provide guidelines for research and clinical use of trip training. The second study (Chapter 3) placed an IMU on the shoulder strap of an undergarment (i.e., a tank top for males and a bra for females) using adhesive wrap, as an alternative to an IMU placed on sternum using the manufacturer-provided chest strap harness. While both change in trunk angle and sternum drop measured by sternum IMU differed between falls and recoveries, only sternum drop measured by shoulder IMU differed between falls and recoveries after the laboratory-induced overground trips. Future studies are necessary to determine the optimal location of an IMU placement for measuring trunk kinematics while maximizing the user comfort and sensitivity to detect differences between falls and recoveries after tripping. In addition, to provide more evidence on the use of sternum drop as a trip recovery kinematic measure, additional studies are needed to investigate how well sternum drop distinguishes falls and recoveries after tripping among other populations with different characteristics. The third study (Chapter 4) demonstrated the feasibility of using IMUs and a voice recorder to understand the underlying mechanisms and context of real-world losses of balance (LOBs). Future studies with larger sample size and longer duration may help better understand differences in tripping kinematics between the laboratory and real world, as well as effectiveness of trip training on reactive balance after real-world LOBs.

Appendices

A. Study 1 (Chapter 2)

Table A.1. Summary of outcome measures. Values are the percentage/counts or least squares means (95% confidence intervals of the means) and *p*-values for *a priori* pairwise contrasts. Positive trunk angle means flexion. Bold indicates statistically significant. BH = Body Height. SH = Sacrum Height.

	NT	TT	CG	NT vs. CG	TT vs. CG	NT vs. TT
Fall rate	24% of 17 trips	63% of 16 trips	50% of 16 trips	0.157	0.722	**0.037**
Stepping strategy (elevating / lowering)	5 / 12	4 / 12	3 / 13	0.688	0.999	0.999
Trunk angle at touchdown (deg)	29.8 (26.1, 33.5)	24.5 (21.0, 28.1)	30.0 (26.4, 33.6)	0.921	**0.027**	**0.039**
Recovery step length (%BH)	49.3 (45.6, 52.7)	45.4 (41.6, 48.9)	40.8 (36.4, 44.8)	**0.002**	0.080	0.112
Recovery step speed (m/s)	1.80 (1.68, 1.91)	1.73 (1.60, 1.84)	1.59 (1.43, 1.73)	**0.022**	0.134	0.358
Distance between mid-hips and step at touchdown (%BH)	14.6 (8.61, 19.5)	12.4 (6.32, 17.4)	8.91 (1.97, 14.8)	0.150	0.386	0.543
Sacrum height at touchdown (%SH)	97.2 (92.7, 101)	101 (96.8, 104)	100 (96.4, 104)	0.241	0.924	0.204

Table A.2. Summary of the *p*-values for all factors considered in the mixed-model ANOVA. Bold indicates statistically significant. BBS = Berg Balance Scale. BH = Body Height. SH = Sacrum Height.

	Group	Trip Number	Trip Outcome	Stepping Strategy	Gait Speed	Pre-Training BBS
Trunk angle at touchdown (deg)	**0.048**	0.540	**0.006**	**0.035**	**0.002**	**0.003**
Recovery step length (%BH)	**0.009**	0.665	0.107	0.598	< **0.001**	0.073

Recovery step speed (m/s)	0.063	0.691	**0.001**	**0.001**	< **0.001**	0.282
Distance between mid-hips and step at touchdown (%BH)	0.342	0.132	< **0.001**	0.149	0.546	0.373
Sacrum height at touchdown (%SH)	0.369	**0.005**	< **0.001**	0.493	0.175	0.725

Table A.3. Clinical tests of balance and mobility. Values are the least squares means (standard errors) and *p*-values for *a priori* pairwise contrasts. Bold indicates statistically significant.

	Time	NT (n = 10)	TT (n = 10)	CG (n = 10)	NT vs. CG	TT vs. CG	NT vs. TT
Timed-up-and-go test (s)	Pre	9.16 (0.54)	10.4 (0.54)	10.3 (0.54)	0.155	0.833	0.104
	Post	9.66 (0.54)	10.3 (0.54)	10.2 (0.54)	0.518	0.855	0.408
Unipedal stance time (s)	Pre	18.9 (4.00)	16.5 (4.00)	17.3 (4.00)	0.787	0.888	0.682
	Post	20.2 (4.00)	15.1 (4.00)	19.6 (4.00)	0.917	0.430	0.372
3-m overground walk test (s)	Pre	1.86 (0.07)	2.08 (0.07)	2.10 (0.07)	**0.017**	0.843	**0.027**
	Post	1.83 (0.07)	1.97 (0.07)	1.94 (0.07)	0.230	0.778	0.140
Berg Balance Scale (score)	Pre	55.1 (0.59)	54.7 (0.59)	53.8 (0.59)	0.123	0.283	0.632
	Post	55.1 (0.59)	55.0 (0.59)	54.6 (0.59)	0.549	0.632	0.905

B. Study 2 (Chapter 3)

Table B.1. Definitions of the two critical temporal events used for trip recovery kinematics calculations. OMC = Optical Motion Capture. IMU = Inertial Measurement Unit.

	Definitions
Trip onset	Time instant at which the tripped foot contacted the trip obstacle, as indicated by the resultant acceleration of the midpoint of the three OMC foot markers or by the resultant acceleration of the foot IMU
Touchdown	Time instant at which the first recovery step over the trip obstacle contacted the walkway, as indicated by the resultant acceleration of the midpoint of the three OMC foot markers or by the resultant acceleration of the foot IMU

Table B.2. Summary of the *p*-values for each factor considered in the mixed-model ANOVA for the first hypothesis. Bold indicates statistically significant.

		Trip outcome	Trip Number	Stepping Strategy	Gait Speed	Berg Balance Test
Change in trunk angle	Sternum IMU	**0.026**	0.307	**0.001**	0.367	0.153
	Shoulder IMU	0.573	0.308	**0.022**	0.406	0.420
	OMC	**0.005**	0.676	**< 0.001**	0.582	0.154
Sternum drop	Sternum IMU	**< 0.001**	0.364	0.274	0.538	0.244
	Shoulder IMU	**< 0.001**	0.546	0.569	0.447	0.299
	OMC	**< 0.001**	0.302	0.185	0.191	0.238

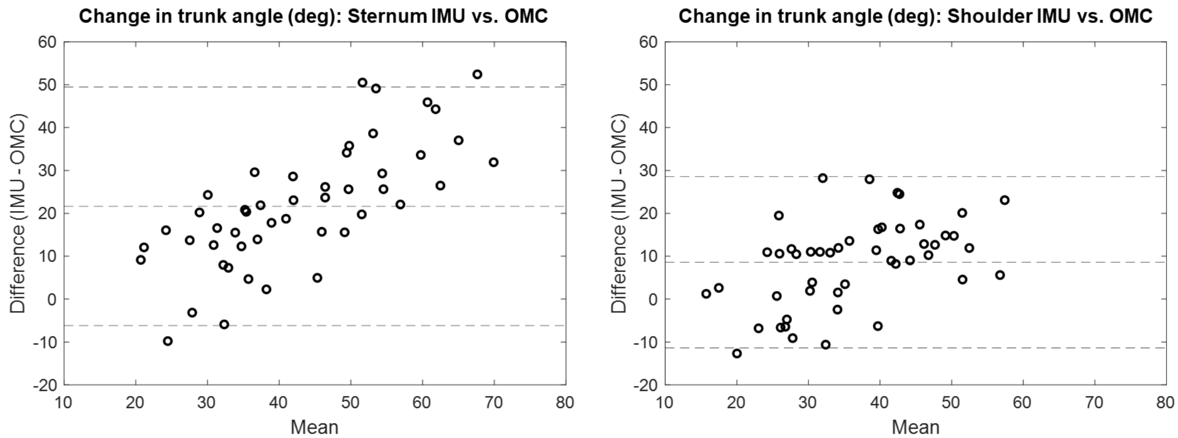

Figure B.1. A Bland-Altman plot showing systematic differences for change in trunk angle between IMUs and OMC. The middle dashed-line is the mean difference. The top and bottom dashed-lines are 95% limits of agreement.

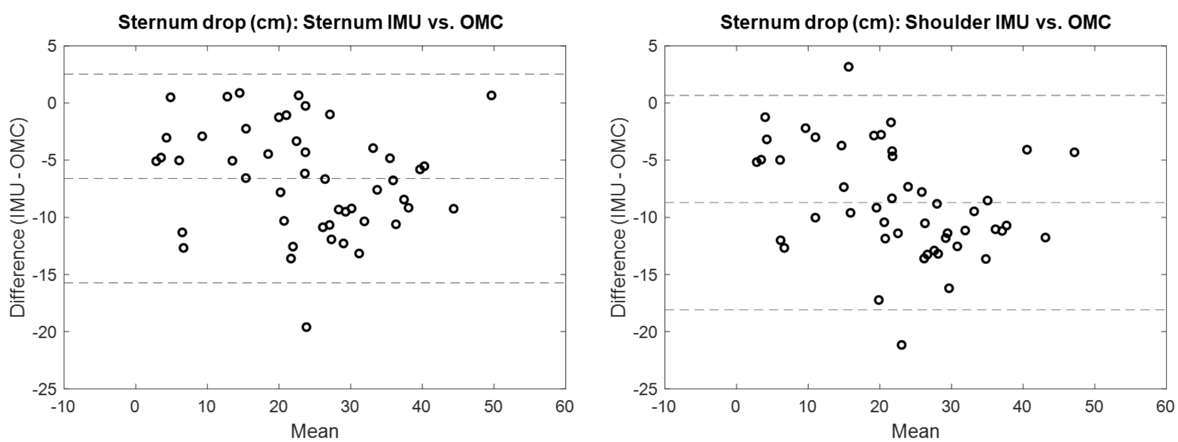

Figure B.2. A Bland-Altman plot showing systematic differences for sternum drop between IMUs and OMC. The middle dashed-line is the mean difference. The top and bottom dashed-lines are 95% limits of agreement.

C. Study 3 (Chapter 4)

Table C.1. The six "4WHO" questions participants were asked to answer during voice recording after each LOB.

Question	Type of answers sought
When did the LOB occur?	Time of day
Where were you when the LOB occurred?	In my kitchen; on the stairs to my basement; in the parking lot of the mall
What were you doing when the LOB occurred?	Walking down my driveway to my mailbox; reaching to the top shelf in my kitchen to get a bowl; going down the stairs
Why do you think you lost your balance?	Slipped on ice; tripped over a door threshold; feet got tangled in dog leash
How did you try to regain your balance?	Took steps; grasped the railing; leaned on the wall
Outcome: Did you recover your balance or fall?	Fell on my knees; recovered my balance without falling

Table C.2. Transcribed voice recordings for the 24 included real-world trips. The real-world trip IDs include an alphabetical letter (assigned for each participant) and a number (assigned for each real-world trip per participant). These IDs are also denoted in Figure 4.4 for comparisons between the tripping kinematics and context of the real-world trips.

Real-world trip ID	Voice recording
a1	I hooked my foot on a leg of a table. It stung a bit, but I caught my balance without needing to hold on to anything. I was in the living room, and I was walking from one room to another.
c1	I just stumbled and almost fell. I was going into my office to do a little bit of work, and the dog decided to come with me and get in front of me, and he crashed into my leg, and I stumbled, but I was able to regain my footing, just you know, I just kept my balance. I didn't grab anything.
d1	I was down in the basement. I was helping clean out lots of clutter and tripped over a strap on the floor where I wasn't looking and just recovered quickly. It was a minor loss of balance and just kind of stepped forward.

d2	I was in my house down in the basement, trying to maneuver between lots of stuff piled everywhere, and tripped with something on my right foot that stopped and quickly caught myself. I was moving from one spot to another, and my right foot caught on something on the floor. I immediately regained my balance by stepping forward and recovered completely. Did not fall and kept on going.
e1	Taking dog on a walk and was coming down a path and meant to step over a branch but caught toe and stumbled forward. Just took a couple steps with left foot but did not fall over. Just a couple recovery steps.
h1	I'm on my morning workout. I did grab a tree limb over here at municipal park around the skate park on the property and my right foot grabbed a tree limb and there was a little bit of a trip incident, but I recovered from the trip. I did not fall, and all is well.
k1	I stumbled at the rec center, walking down a kinda sticky floor, caught a toe, or really the ball of my foot, grabbed my balance very quickly after that, and so all is well, did not fall, just caught a toe, that was it.
n1	I just tripped on the wheel of the lawnmower while I was working in the tunnel, but I raised my foot up over it and I did not fall.
n2	I just had an incident where I tripped on a rug standing pad in our kitchen. I just clipped my toe against the end of it and stumbled a little bit and it was my left root that hit the rug and I corrected with a nice big step and did not fall.
p1	I stumbled slightly, as I was in the kitchen, and hit foot on the corner of the net. I did not fall. I just caught myself in stride and kept going.
q1	I was walking at the rec center. You can probably hear some of the noise of the people in the background here. We're going around the corner. I started to trip, and my left foot caught in the track, and I think that's what caused me to lose my balance. I was able to regain it by taking a fast step with my right leg, and the outcome was that I was able to recover and keep on going.
q2	I have been walking on a sidewalk in the neighborhood, and it had rained overnight so it was moist. I came into our house, and I didn't think about it but the bottom of my shoes were wet and as I stepped onto the wooden floor in our dining room I caught my left foot and it adhered to the floor, and I started to lose my balance but by taking an extra step with my right foot I was able to regain it, so the outcome is that I recovered and am doing okay.

r1	I was just putting groceries away, walking across my wooden floor in the kitchen, and the front part of my shoes with rubber sole just hit onto the wood and, uh, stumbled just very briefly, and I just lifted my foot and put it down the right way to regain my balance, so it was fine.
r2	I just tripped. I was walking on our road, with my big dog, and a car passed me and the dog kinda bumped, went in front of me, and my foot hit his foot, so I tripped, but I just caught myself right away. I was looking down at my phone when I was walking, and when the dog moved over into me, my foot hit his foot and knocked my foot into my other foot, and that’s how I tripped. Just slightly.
r3	I’m in the grocery store and when I walked by something that had a little shelf sticking out, my foot hit it, and I tripped just slightly.
r4	I’m shopping in a store, and my right foot, uhm, it hit the floor and stuck or whatever, things that happen sometimes, and I stumbled a little bit, but nothing major.
r5	Once again, I’m in a different store, and uhm, it’s this kinda polished concrete just like the other, then again, this shoe hit, and it’s raining outside which might have something to do with it. This shoe kinda stuck on the floor when I was walking, made me stumble just a little bit. My right foot again.
s1	I tripped over a pole I couldn’t see, it’s nighttime, and I’m out at a little party that was outside. But, my little trip recovery thing, I just tripped, I recovered, and it was awesome.
w1	I tripped over a doorstop in my bedroom, recovered with no problem, didn't touch anything, didn't fall down, but I did trip over it with my left foot, just didn't see it was there.
x1	Walking out on my patio, stumbled on a brick that was laying at the corner of the patio with my left foot, regained balance, no problem
x2	Caught my leg on a walker on my father's right leg, and stumbled just a bit, regained balance no issues, just stumbled.
z1	I was walking down a ramp and tripped on the edge. Just took an extra step to correct myself. I feel completely fine and regained my balance quickly.
z2	I just stubbed my toe on the door sill on the way into the house at home, so nothing major, took another quick step and I’m fine.

z3	I just caught my toe on the cord of a vacuum cleaner and took an extra step. I don’t think I was in danger of falling but just in case, I wanted to make sure I had a stable base. So that was here, on the farm in the workshop, and that was it. I’m fine.