PHYSICAL ACTIVITY, MUSCLE QUALITY, AND REACTIVE BALANCE CONTROL IN COMMUNITY-DWELLING OLDER ADULTS

by

Justin Mark Moeller Whitten

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Exercise and Nutrition Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

May 2025

ACKNOWLEDGMENTS

First, I want to thank my former primary advisor, Dr. David Graham. You have been an incredible mentor, both professionally and personally, throughout this journey. Thank you for all the guidance, support, and coffee over the last seven years. To Dr. Dawn Tarabochia, your enthusiasm and passion for teaching inspired me to pursue this degree, and for that, I will always be grateful. To Dr. Michelle Grocke, thank you for allowing me to branch into Extension and community-based research. To Dr. John Seifert, your unique perspective and depth of experience in both research and life provided much-needed balance in this final year, thank you. Beyond my advisors, there are too many people who have helped me along the way to name them all, but I want to especially acknowledge the friends and colleagues who have been part of this journey: Leah, Bryant, Cailyn, Jeremy, Jenni, Morgan, Meghan, and Stephanie, thank you for your friendship and support. I wouldn’t be the person I am today without you. Finally, to my family—thank you for your never-ending love and support over these last seven years. Even when this work took me away from being the husband, son, and grandson I wanted to be, you were always there. I couldn’t have done this without you.

Thank you.

TABLE OF CONTENTS

1. INTRODUCTION 1

The Growing Burden of Falls 1
Why Do Older Adults Fall? 2
Conventional Balance Training 3
Perturbation-Based Balance Training 4
Purpose 5

2. BASELINE MEASURES OF PHYSICAL ACTIVITY AND FUNCTION DO NOT PREDICT FUTURE FALL INCIDENCE IN SEDENTARY OLDER ADULTS: A PROSPECTIVE COHORT STUDY 6

Contributions of Authors and Co-Authors 6
Manuscript Information 7
Abstract 8
Introduction 8
Methods 9
  Participants 9
  Recent Minor Musculoskeletal Injury 9
  Physical Function 9
  Lower Limb Strength 9
  Physical Activity Monitoring 9
  Fall Monitoring 9
  Statistical Analysis 10
Results 10
  Falls Incidence 10
  Fall Status and Measures of PA and PF 10
  Fall Status and Prior Minor Injury 10
Discussion 10
  Fall Incidence, PA, PF, and LLS 10
  Falls Status and Prior Minor Musculoskeletal Injury 11
  Strengths and Limitations 11
Conclusion 11
Acknowledgements 11
References 11

3. MUSCLE QUALITY AND REACTIVE BALANCE CONTROL IN OLDER AND YOUNGER ADULTS 13

Contributions of Authors and Co-Authors 13
Manuscript Information 14
Abstract 15

TABLE OF CONTENTS CONTINUED

Introduction 16
Methods..17
Participants 17
Muscle Quality Assessment 18
Balance Control Assessments 18
Maximum Recoverable Lean Magnitude 18
Choice Step Reaction Time – Modified 19
Statistical Analysis 20
Results 20
Comparison of Older and Younger Participants 20
Analysis of Older Participants 22
Discussion 22
Muscle Quality and Balance Control 23
The Predictive Value of Muscle Quality in Older Adults 24
Practical Implications 24
Considerations and Future Directions 25
Conclusion 25
References 26

4. THE ACCEPTABILITY OF COMMUNITY-BASED PERTURBATION-BASED BALANCE TRAINING TO OLDER ADULTS AND HEALTHCARE PROFESSIONALS 29

Contribution of Authors and Co-Authors 29
Manuscript Information 30
Abstract 31
Introduction 31
Methods 33
Context 33
PBT Protocol 33
Participants 33
Data Collection Procedures 33
Analytical Procedures 34
Coding 34
Triangulation and Reflexivity 35
Results 35
Participants 35
Acceptability 35
Affective Attitude 35
Older Adults 35
HCPs 36

TABLE OF CONTENTS CONTINUED

Burden 37
Older Adults 37
HCPs 37
Ethicality 37
Older Adults 37
HCPs 38
Intervention Coherence 38
Older Adults 38
HCPs 38
Opportunity Cost 38
Older Adults 38
HCPs 39
Perceived Effectiveness 39
Older Adults 39
HCPs 39
Self-Efficacy 39
Older Adults 39
HCPs 40
Discussion 40
Facilitators of Acceptability 40
Community Education 40
Barriers to Acceptability 41
PBT Equipment 41
Older Adults 41
Healthcare Providers 41
Conclusion 42
References 42

5. CONCLUSION 44

Summary of Key Findings 47
Physical Activity and Future Falls 47
Muscle Quality and Reactive Balance Control 48
The Acceptability of PBT 49
Specificity is King: Why General Methods Aren't More Effective 50
Understanding Balance Control 50
Key Subsystems of Balance Control 51
Where Conventional Balance Training Falls Short 52
Perturbation-Based Balance Training 53
Implications and Future Directions 54
Strengths and Limitations 56
Strengths 56

TABLE OF CONTENTS CONTINUED

Limitations 57
Conclusion 58

6. CUMULATIVE REFERENCES CITED 60

LIST OF TABLES

Table Page

1. Table 1 Summary Data for Baseline Demographic, PA, PF, LLS, and Prior Injury Stratified by Prospective Fall Status 10
2. Table 2 Participant Characteristics 21
3. Table 3.1 Theoretical Framework of Acceptability 32
4. Table 3.2 TFA Components, Interpretations, and Related Questions 34
5. Table 3.3 Participant Characteristics 35
6. Table 3.4 Summary of Findings 36

LIST OF FIGURES

Figure Page

1. Figure 1.1 Example sequence of a participant completing the tether release balance recovery task while kinematic and kinetic data are recorded 19

2. Figure 1.2 CSRT-M mat. The white boxes are the start boxes, and the gray boxes are the target boxes. Dimensions are in cm. 19

3. Figure 1.3 Biceps femoris muscle quality (arbitrary units) vs Maximum Recoverable Lean Magnitude (degrees), Figure 3A includes the outlier, and Figure 3B depicts the relationship with the outlier removed. 22

4. Figure 2 PBT treadmill 33

ABSTRACT

Falls are a leading cause of injury, disability, and mortality among older adults, yet existing fall prevention strategies have not effectively reduced fall rates. Despite widespread recommendations promoting general physical activity and conventional balance training, falls and fall-related deaths continue to increase. One potential reason for this limited success is that conventional interventions primarily focus on proactive balance control and functional capacity, while most falls arise from unexpected perturbations that necessitate rapid reactive balance responses. Perturbation-based balance training (PBT) has emerged as a promising strategy to improve reactive balance control and lower fall risk, but its feasibility, effectiveness, and broader implementation remain insufficiently explored. Through three studies, this dissertation investigated key factors contributing to fall risk and balance recovery in older adults. Study 1 examined whether habitual physical activity and conventional functional assessments can predict future falls in community-dwelling older adults. Results showed no significant association, suggesting that traditional measures may not adequately capture the neuromuscular mechanisms crucial for fall prevention. Study 2 explored the link between lower limb muscle quality and balance recovery, finding that biceps femoris muscle quality was related to improved reactive balance responses. This preliminary evidence underscores the potential role of muscle composition in assessing fall risk. Study 3 evaluated the acceptability and feasibility of a community-based PBT program, revealing that while older adults and healthcare providers regarded PBT as beneficial, cost and accessibility posed barriers to widespread adoption. Collectively, these findings reinforce the need for a paradigm shift in fall prevention, emphasizing targeted assessments and interventions that specifically enhance reactive balance control. Future research should focus on refining assessment tools, optimizing PBT protocols, and developing cost-effective methods for integrating reactive balance training into clinical and community settings. Addressing these gaps is essential for advancing fall prevention strategies and improving outcomes for older adults at risk of falls.

CHAPTER ONE

INTRODUCTION

The Growing Burden of Falls

Falls are a leading cause of morbidity and mortality among older adults, with over 14 million adults over the age of 65 experiencing a fall each year in the United States [1]. Falling once doubles the likelihood of future falls[2], and those who have experienced multiple falls face an elevated risk of mortality[3]. Falls are responsible for over 95% of hip fractures[4] and are the leading cause of traumatic brain injuries in the U.S.[5]. Approximately one in four older adults in the U.S. and one in three worldwide experience a fall each year [6].

Beyond their impact on individuals, falls place a substantial strain on healthcare systems. In the U.S., falls result in over three million emergency department visits and more than 800,000 hospitalizations annually[6]. The financial burden is significant, with medical costs ranging from $1,000 to $3,000 per fall, and the treatment of injurious falls requiring up to 284 additional healthcare worker hours at an estimated cost of over $10,000 per case[7]. In 2015 alone, the total medical cost of falls in the U.S. reached $50 billion, with Medicare and Medicaid covering the majority of expenses[8].

The aging population further amplifies the urgency of addressing fall prevention. In 1920, older adults comprised 1 in 20 Americans; by 2020, they accounted for 1 in 6, a trend that will continue as the population grows. The number of older adults in the U.S. is expected to increase by 47%, from 58 million in 2022 to 82 million by 2050, raising their share of the total population from 17% to 23%[9]. Despite increased public health efforts, fall-related deaths among older adults have risen by 41% in the past decade[10], underscoring the need for improved fall prevention strategies.

Why Do Older Adults Fall?

Falls occur due to a loss of balance from which an individual cannot recover. While both younger and older adults experience loss of balance, older adults fall more often due to a diminished ability to regain balance[11–18]. Diminished balance control among older adults is generally attributed to age-related deficits in sensorimotor function[19,20]. Deficits may vary based on the individual but, in general, include declines in reaction time, proprioception, vestibular function, muscle quality, and visual deficits[19]. These general age-related declines in sensorimotor function result in an elevated fall risk among older adults. Many factors contribute to fall risk; these factors are typically categorized as either intrinsic or extrinsic risk factors.

Extrinsic risk factors are related to the environment in which the fall occurred. Such risk factors include inclement weather, poor lighting, cluttered walkways, and poor choice of footwear. Conversely, intrinsic risk factors are related to the individual who experienced the fall. Intrinsic risk factors include chronic health conditions such as Parkinson's disease, Alzheimer's, or dementia, as well as visual impairment and polypharmacy[21]. Individuals can address extrinsic factors to a certain extent (i.e., wearing appropriate footwear and ensuring lighting within their home). Although, in many cases, extrinsic factors cannot be addressed on a meaningful scale. Many intrinsic risk factors, such as polypharmacy, visual impairment, and certain chronic health conditions, are not modifiable. Physical activity and function have been repeatedly linked to retrospective fall incidence[22,23] and poor or disordered balance is one of the primary causes of falls in older adults[24]. Accordingly, many fall prevention programs target risk factors that are meaningfully modifiable, such as physical activity, physical function, and balance[25,26].

Conventional Balance Training

Conventional Balance Training (CBT) is commonly recommended by public health institutions such as the Department of Health and Human Services and the American College of Sports Medicine. CBT generally consists of volitional static or quasi-static exercises such as tandem stance or walking, single leg stance, heel or toe walking, standing on progressively unsteady surfaces, etc., in some instances, conventional balance training may also include resistance training, typically focused on lower limb and trunk musculature[26–29]. It's widely accepted that CBT can improve balance control and has been reported to reduce fall rates in older adults by approximately 24%[29,30]. However, there are some potential drawbacks to CBT programs that may limit their efficacy in terms of fall risk reduction.

To understand these potential drawbacks, it is first necessary to clarify that 'balance control' is an umbrella term that can be divided into several different motor skills[31], each of which serves its specific role during activities of daily living. The three domains of balance control, as described by Berg et al., include static balance control (the ability to maintain balance in a static position), proactive balance control (the ability to make voluntary anticipatory adjustments to maintain balance), and reactive control (the ability to recover from unexpected perturbations to balance)[31]. As conventional balance training programs are primarily composed of static voluntary balance exercises, they typically train only static and proactive balance control[26,29]. Notably, about 60% of falls experienced by older adults result from an external perturbation to balance such as a slip or a trip[32,33]. Given that the ability to generate a balance recovery response following an external perturbation is governed by reactive balance control, the efficacy of conventional balance training may be limited by its apparent lack of specificity[34,35].

Perturbation-Based Balance Training

Perturbation-based balance training (PBT), also known as reactive balance training, is a training paradigm designed to improve reactive balance control by exposing participants to controlled external perturbations. Unlike conventional balance training, which primarily targets proactive balance control through voluntary postural adjustments, PBT aims to enhance the rapid, automatic responses required to recover from real-world balance disruptions such as slips or trips[35–39].

Studies have demonstrated that PBT can significantly reduce fall risk. Participation in PBT has been associated with a lower incidence of laboratory-induced falls[40–42] and improvements in key balance recovery measures such as stepping responses and postural adjustments[43,44]. Additionally, two meta-analyses have reported that PBT reduces prospective fall rates by approximately 50%, nearly doubling the reduction observed with conventional balance training[45,46]. Furthermore, early findings suggest that PBT may be effective at a lower training dose than conventional balance training, with some studies demonstrating meaningful improvements in balance recovery after just one session[35,47,48].

Despite these promising outcomes, several challenges must be addressed before PBT can be widely implemented as a fall prevention strategy. A major limitation in the current literature is the heterogeneity of PBT interventions. Studies differ in the type, intensity, and volume of perturbations used, making it difficult to determine the optimal training parameters. This variability also complicates comparisons between studies and raises questions about the generalizability of findings to different populations, including older adults with varying functional abilities. Additionally, while laboratory-based improvements in balance recovery are well-documented, further research is needed to determine the extent to which these gains transfer to real-world fall prevention.

Another important consideration is the feasibility and acceptability of PBT. The unpredictable nature of perturbations may initially be physically or psychologically challenging for some older adults, potentially leading to anxiety or fear of falling. Although some studies suggest PBT may not be tolerable for all individuals[49,50], there has been little direct research assessing older adults' perceptions of PBT. Understanding participant experiences, including comfort, safety, and willingness to engage, is crucial for developing interventions that are both effective and widely adopted[51].

Purpose

The purpose of this dissertation is to examine key contributors to reactive balance control and fall risk in community-dwelling older adults and assess the feasibility of targeted interventions to improve balance recovery and reduce fall risk. To achieve this, three specific aims were developed: (1) Investigate the relationship between habitual physical activity and prospective fall incidence in community-dwelling older adults, (2) Examine the role of lower limb muscle quality in balance recovery and reactive balance control, and (3) Evaluate the acceptability of a community-based perturbation-based balance training program for older adults in Montana.

CHAPTER TWO

BASELINE MEASURES OF PHYSICAL ACTIVITY AND FUNCTION DO NOT PREDICT FUTURE FALL INCIDENCE IN SEDENTARY OLDER ADULTS: A PROSPECTIVE COHORT STUDY

Contribution of Authors and Co-Authors

Manuscript in Chapter 2

Author: Justin Whitten

Contributions: Involved in the initial conception of the study and statistical analysis. Primarily responsible for data and analysis and preparing the initial draft of the manuscript.

Co-Author: Dr. Rod Barrett

Contributions: Responsible for organization and oversight of data collection as well as providing mentorship and feedback during the manuscript writing process.

Co-Author: Dr. Christopher Carty

Contributions: Responsible for organization and oversight of data collection.

Co-Author: Dr. Dawn Tarabochia

Contributions: Involved in developing data analysis methods and manuscript preparation.

Co-Author: Dr. David MacDonald

Contributions: Responsible for organization and oversight of data collection.

Co-Author: Dr. David Graham

Contributions: Responsible for organization and oversight of data collection as well as providing feedback during the manuscript writing process.

Manuscript Information

J. Whitten, R. Barrett, C. Carty, D, Tarabochia, D. MacDonald, and D. Graham

Status of Manuscript:
☐ Prepared for submission to a peer-reviewed journal
☐ Officially submitted to a peer-reviewed journal
☐ Accepted by a peer-reviewed journal
☒ Published in a peer-reviewed journal

Journal of Aging and Physical Activity
Published: November 28, 2023
Volume 32: Issue 2
DOI: https://doi.org/10.1123/japa.2022-0355

Journal of Aging and Physical Activity, (Ahead of Print)
https://doi.org/10.1123/japa.2022-0355

First Published Online: Nov. 28, 2023

Human Kinetics
ORIGINAL RESEARCH

Baseline Measures of Physical Activity and Function Do Not Predict Future Fall Incidence in Sedentary Older Adults: A Prospective Cohort Study

Justin Whitten,[1] Rod Barrett,[2] Christopher P. Carty,[2,3] Dawn Tarabochia,[1] David MacDonald,[2] and David Graham[1,2]

[1]Department of Health and Human Development, Montana State University, Bozeman, MT, USA; [2]School of Health Sciences and Social Work and Griffith Center for Biomedical and Rehabilitation Engineering, Menzies Health Institute Queensland, Griffith University, Gold Coast, QLD, Australia; [3]Department of Orthopedics, Children's Health Queensland Hospital and Health Service, Brisbane, QLD, Australia

Physical activity (PA) and physical function (PF) are modifiable risk factors for falls in older adults, but their ability to predict future fall incidence is unclear. The purpose of this study was to determine the predictive ability of baseline measures of PA, PF, and lower limb strength on future falls. A total of 104 participants underwent baseline assessments of PA, PF, and lower limb strength. Falls were monitored prospectively for 12 months. Eighteen participants fell at least once during the 12-month follow-up. Participants recorded almost exclusively sedentary levels of activity. PA, PF, and lower limb strength did not differ between fallers and nonfallers. Twelve participants, who reported a minor musculoskeletal injury in the past 6 months, experienced a fall. The results of this study suggest that in a cohort of highly functioning, sedentary older adults, PA does not distinguish fallers from nonfallers and that the presence of a recent musculoskeletal injury appears to be a possible risk factor for falling.

***Keywords**:* balance, accelerometers, risk factors, fall risk, mobility

Key Points

- Physical activity did not differentiate fallers and nonfallers in a cohort of sedentary older adults.
- Minor musculoskeletal injury such as a sprain strain or minor fracture may be an early warning of elevated falls risk in sedentary older adults.

Falls are a leading cause of severe injuries in older adults including hip fractures (Hayes et al., 1993) and traumatic brain injuries (Jager et al., 2000). It is estimated that one in four adults over the age of 65 experience a fall each year (Bergen et al., 2016). Falls among older adults represent a major global public health concern (James et al., 2020), contribute to high hospitalization rates (Australian Institute of Health and Welfare, 2022), and substantial financial burden at all levels of health care systems (Florence et al., 2018; Hoffman et al., 2022). There are many documented risk factors for falling including previous falls, balance impairment, decreased muscle strength, and functional limitations (Tinetti & Kumar, 2010), such as those that may occur as a result of injury and inactivity.

We have previously demonstrated that reactive stepping behavior to a forward loss of balance and the Physiological Profile Assessment (Lord et al., 2003) were predictive of prospective falls in this same cohort of community-dwelling older adults (Carty et al., 2015). While these assessments of fall risk were effective in terms of fall prediction, their utility in community and clinical settings is likely limited due to the time, expertise, and equipment required to conduct them. Alternatively, factors such as physical function (PF), physical health limitations, and physical activity (PA) can all be assessed by clinicians with relative ease. For instance, PF is often assessed using measures of strength and mobility such as dynamometry or the Timed Up and Go (TUG), respectively. While physical health limitations can be accessed via questionnaires such as the Baecke Questionnaire and the Short-Form 36 Item (SF-36) Survey. PA may be defined as any bodily movement that requires energy expenditure and refers to all movement including movement during leisure time, transport, or as part of a person's work. PA can be assessed in a variety of low-effort methods including self-report questionnaires or the use of pedometers and accelerometers.

Previous investigations of the relationship between PA and falls in older adults have tended to use indirect, self-reported measures of PA and are often retrospective in nature (Sun et al., 2013). For instance, Chang and Do (2015), found higher levels of self-reported PA were protective against falls in older men and women. Similarly, Moreira et al. (2018) found that lower self-reported PA and functional mobility (TUG score) were associated with an increased retrospective fall incidence in older adults. The retrospective design of those studies makes it difficult to determine whether lower PA contributes to falls, if prior falls lead to a subsequent decline in PA, or whether another factor (such as illness or injury) could lead to a reduction in both PA and falls.

Barrett https://orcid.org/0000-0002-1784-1629
Carty https://orcid.org/0000-0002-8969-5181
Tarabochia https://orcid.org/0000-0002-6278-6569
MacDonald https://orcid.org/0000-0003-2638-0788
Graham https://orcid.org/0000-0001-7338-3995
Whitten (justinwhitten@montana.edu) is corresponding author, https://orcid.org/0000-0002-2237-0462

Studies that have prospectively examined the relationship between falls incidence and PA have led to contradictory conclusions. For example, in an investigation of the relationship between PA and fall incidence, Klenk et al. (2015) found no overall association between PA level and falls per person year. However, that study also reported less active older adults experienced significantly more falls per hour walked compared with their more active counterparts. In a similar investigation, Okubo et al. (2016) found participation in a 16-month walking program led to a significant reduction in fall risk per person step compared to an active control group. Those authors also found that the presence of two or more falls risk factors modulated the association between habitual walking and falls history (Okubo et al., 2015), walking increased fall risk in high-risk older adults, and decreased fall risk in low-risk older adults. Although those results taken together suggest PF may influence the relationship between habitual PA and fall risk, a recent systematic review concluded there was a high level of uncertainty regarding the evidence for habitual PA and reduced prospective falls risk (Sherrington et al., 2020).

To our knowledge, no prior study has prospectively investigated the relationship between falling and direct estimates of PA and PF. Therefore, the purpose of this investigation was to determine the ability of baseline measures of PA and function to predict prospective fall incidence in a cohort of community-dwelling older adults.

Methods

Participants

Data for this study were collected from February 2010 to August 2013. One hundred and four community-dwelling older adults, above the age of 65 (50 men and 55 women; mean [*SD*]; age: 71.8 [4.92] years; height: 1.7 [0.09] m, mass: 74.8 [13.2] kg) were randomly contacted from the local electoral roll. Individuals who had previously been diagnosed with any major neurological, cardiopulmonary, metabolic, musculoskeletal, or visual conditions/impairments that would be reasonably expected to adversely influence their motor function were excluded. Ethics approval was obtained from the Institutional Human Research Ethics Committee and all relevant ethics guidelines including provision of informed consent were followed.

Recent Minor Musculoskeletal Injury

As a part of the normal screening process, volunteers were also asked if they had experienced any minor musculoskeletal injuries such as muscle, ligament or tendon strains, sprains, or tears of any kind within the last 6 months.

Physical Function

Prior to the activity monitoring period, participants completed a baseline assessment including medical history as well as questionnaires and surveys regarding their overall health and habitual activity level. The SF-36 Survey (version 1.0, QualityMetric) and the Baecke questionnaire (Baecke) were used to assess the overall health status of the participants and identify mobility limitations (Syddall et al., 2009). Participants answered questions regarding habitual PA levels to provide a self-reported measure of PA level (low, moderate, and high activity; Baecke et al., 1982). The TUG (Podsiadlo & Richardson, 1991) was completed by participants to assess their general mobility.

Lower Limb Strength

Lower limb maximal voluntary isometric strength was assessed as described by Carty, Cronin, et al. (2012). Briefly, lower limb maximum voluntary isometric strength was assessed at baseline, across the joint range of motion, for the ankle, knee, and hip flexors and extensors using an isokinetic dynamometer (Biodex System 4, Biodex Medical Systems). Participants completed submaximal practice trials at the second angle for each joint, until investigators were confident the participant was able to produce maximal effort. Strength measurements were first taken distally, at the ankle, and progressed proximally, to the hip, and were progressed from greater flexion angles to lesser flexion angles. Participants completed two maximum voluntary flexion and extension trials for each joint and joint angle combination. Trials were for 3 s and participants were instructed to flex or extend the joint "as hard as they could" for the whole trial. Investigators gave verbal encouragement throughout the trial to maximize effort. Participants rested for 60 s between trials. For ankle strength measurement, subjects were seated with arms resting on their thighs, with their hips and knees in 90° and 60° of flexion, respectively. Ankle strength was assessed at 0°, 15°, and 30° of flexion as well as end range of motion in dorsiflexion and plantarflexion. For knee strength measurement, participants remained seated with hands on thighs with hips at 70° of flexion and the ankle in 5° of plantar flexion. Knee strength was assessed at 30°, 60°, and 90° of knee flexion, as well as end range of motion in extension. Hip strength measurements were taken with subjects in a standing position, the knee was constrained to a 60° flexion angle using a postsurgical knee brace. A custom frame was used to stabilize the contralateral limb as well as the upper body during the measurement of hip strength. Hip strength was measured at 10°, 40°, and 70° of flexion, as well as end range of motion in flexion and extension. Based on the recommendations of Kellis and Baltzopoulos (1996), isometric joint moments were adjusted to account for the weight of the dynamometer. Data from Dempster (1955) were used to estimate body segment parameters. A moment angle curve was created for each joint, in each direction, by a second-order polynomial fitted to the data. Isometric strength for each joint in each direction was defined as the peak value on the moment angle curve.

Physical Activity Monitoring

PA data were collected for all participants via hip worn ActiGraph-GT3X+ triaxial accelerometers (ActiGraph). Participants were instructed to wear accelerometers for seven consecutive days (Sasaki et al., 2017). Accelerometers were worn continuously throughout the monitoring period except for during activities such as bathing and getting dressed.

Accelerometer data were collected at 30 Hz, and all accelerometer outputs are based on data collected from the vertical axis. Custom MATLAB scripts (R2018b; MathWorks) were used to calculate total step count per day as well as counts per minute. Counts per minute were used in conjunction with age-specific cut point ranges to determine time spent at each level of PA intensity. Four age-specific cut points were used to differentiate between sedentary (<25; Aguilar-Farias et al., 2014), light (25–809), moderate (809–1,013; Hall et al., 2013), and vigorous (>1,013; Barnett et al., 2016) levels PA.

Fall Monitoring

Following completion of activity monitoring, participants were provided with a monthly fall diary containing questions related to falls and injuries. A fall was defined as "an unexpected event in which the participant came to rest on the ground, floor, or lower level" (Lamb et al., 2005). If a fall was experienced, participants were instructed to complete the questions as soon as possible within the month in which the fall occurred. Participants were contacted via phone by a member of the research team once a month for 12 months to collect fall data. Participants were subsequently classified as either fallers or nonfallers based on whether they experienced a fall during the 12-month fall monitoring period.

Statistical Analysis

General linear models with sex as a covariate were used to assess the association between normalized joint-specific strength, PA, TUG, prior injury status, recent fall history, SF-36, Baecke, body mass index, and age, respectively. Statistical analyses were performed using R Statistical Software (v4.1.3, R Core Team). Significance was accepted for $p < .05$.

Results

Falls Incidence

Eighteen participants (17%) experienced one or more falls during the 12-month prospective follow-up period (Table 1). Of the 18 participants who experienced a fall, 12 fell once, four fell twice, and two fell three times (26 falls in total were recorded).

Fall Status and Measures of PA and PF

All measures of lower limb strength (LLS) as well as height and body mass were significantly different between male and female participants in this cohort. Therefore, sex was added as a control variable to the primary analysis. After controlling for the effects of sex on fall incidence, no significant group differences were detected in average percentage of time spent in sedentary activity levels, SF-36, Baecke, TUG, and lower limb isometric muscle strengths between fallers and nonfallers (all p's $> .05$). All participants spent time in sedentary and light levels of activity and no participant recorded any moderate or vigorous PA.

Fall Status and Prior Minor Injury

Twelve participants reported a minor musculoskeletal injury within the 6 months prior to their initial screening. Minor injuries reported by participants included minor fractures and soft tissue injuries such as sprains, strains, and minor tears. All 12 of these participants reported a fall during the 12-month monitoring period. Prior injury status was the only variable that significantly differed between fallers and nonfallers ($p < .001$) and, as such, was the only variable eligible for entry into the stepwise model selection process. The model selection process revealed that prior injury status was a significant predictor of prospective falls ($p < .001$, $R^2 = .37$).

Discussion

This prospective cohort study found no association between baseline measures of PA, PF, and LLS and prospective fall incidence, in a cohort of 104 highly functioning, largely sedentary, community-dwelling older adults. Second, the presence of a prior musculoskeletal injury such as a sprain, strain, or minor fracture, in sedentary older adults with high levels of PF may be an early warning of falls risk and may need to be considered as a potential risk factor for falling.

Table 1 Summary Data for Baseline Demographic, PA, PF, LLS, and Prior Injury Stratified by Prospective Fall Status

Fall status	Nonfaller	Faller	p
Demographics			
n	86	18	na
Sex (female/male) (% female)	45/41 (52%)	9/9 (50%)	na
Age (years)	71.9 ± 5.0	71.1 ± 4.7	.51
BMI (kg/m^2)	26.7 ± 3.5	27.4 ± 4.1	.44
Body mass (kg)	74.1 ± 12.8	78.1 ± 15.1	.24
Height (m)	1.66 ± 0.09	1.68 ± 0.08	.39
Injury status			
Prior injury, count (%)	0 (0%)	12 (67%)	<.001
PA level			
Total counts	10,057 ± 12	10,056 ± 6	.97
Vigorous (% total counts)	0	0	na
Moderate (% total counts)	0	0	na
Light (% total counts)	5 ± 3	6 ± 2	.36
Sedentary (% total counts)	95 ± 2	94 ± 2	.34
PF			
Baecke	8 ± 5	9 ± 6	.58
SF-36 total	79 ± 17	84 ± 9	.25
Physical subscore	76 ± 17	80 ± 11	.29
Mental subscore	80 ± 17	82 ± 11	.51
TUG (s)	6.0 ± 1.0	6.1 ± 1.0	.55
LLS (N·m)			
Hip flexion	80.3 ± 27.3	81.0 ± 28.8	.92
Hip extension	105.9 ± 33.9	111.7 ± 34.4	.51
Knee flexion	70.9 ± 21.8	71.3 ± 23.7	.96
Knee extension	78.5 ± 30.7	76.5 ± 26.9	.79
Ankle dorsiflexion	30.1 ± 8.9	30.9 ± 10.9	.73
Ankle plantarflexion	77.9 ± 32.8	72.7 ± 34.9	.55

Note. T tests were used to calculate all *p* values. Data are reported as mean ± *SD*. PA = physical activity; PF = physical function; SF-36 = Short-Form 36 Item; BMI = body mass index; TUG = Timed Up and Go; LLS = lower limb strength.

Fall Incidence, PA, PF, and LLS

Our result that PA did not differ between fallers and nonfallers is supported by previous reports that have demonstrated leisure activities (Chan et al., 2007), general PA such as walking (Sherrington et al., 2020), and low amounts of moderate activity and low-intensity PA alone (Dipietro et al., 2019) do not appear to be protective against falls. It has been demonstrated that structured multicomponent (functional and balance exercises) exercise programs can effectively reduce fall risk (Dipietro et al., 2019; Sherrington et al., 2020). Although older adults' preference to use low-intensity activities, such as walking (Amireault et al., 2019), as their primary form of activity, may present a potential challenge to participation in such programs (Rivera-Torres et al., 2019). Therefore, we suggest that future studies should investigate the barriers, benefits, and acceptability of more specific, higher intensity fall prevention programs for older adults.

We also found no group difference in measures of PF (the TUG, SF-36, and Baecke) and LLS between fallers and nonfallers. This result was somewhat surprising considering previous reports of poor PF and muscle weakness as established risk factors for falling (Tinetti & Kumar, 2010). One possible reason for the lack of group difference in PF and strength between fallers and nonfallers may be the relatively high functional capacity of the participants in the present study. To be eligible for the present study, participants were free from any diagnosed neurological, cardiopulmonary, metabolic, and/or musculoskeletal conditions and had relatively high levels of PF, as indicated by TUG scores, which were well below the recommended fall prediction cutoff of 13.5 s (Shumway-Cook et al., 2000). The observed fall rate of 17% was also considerably lower than a recent estimate of fall rates for older adults in Oceania of 34% (Salari et al., 2022). Similar relationships have been reported between functional capacity and fall risk in other populations. For instance, Sheehan et al. (2022) reported functional performance measures and temporal-spatial gait parameters were not associated with fall risk in young, high functioning individuals with lower limb trauma, despite a high number of reported falls.

Previous investigations involving this same cohort of community-dwelling older adults demonstrated that greater LLS was associated with improved balance recovery performance (Carty, Barrett, et al., 2012; Carty, Cronin, et al., 2012), and that balance recovery performance was predictive of prospective falls (Carty et al., 2015). While LLS is associated with balance recovery performance, and balance recovery performance is associated with fall incidence, the current findings suggest that strength of the lower limb muscles is not associated directly with falls. We; therefore, suggest that once an individual attains a minimum threshold of muscular strength and PF, the intrinsic risk factors that influence fall incidence such as the ability to rapidly generate muscle force and coordinate balance recovery responses may be better predictors of falls than muscle strength alone. Indeed, studies conducted in the same participant cohort as the present study have revealed that lower limb joint power production is a better predictor of balance recovery performance than muscular strength (Graham et al. 2014), and that the muscle recruitment and coordination strategy associated with successful balance recovery by stepping is readily distinguished from unsuccessful attempts to recover balance (Carty, Barrett et al., 2012; Cronin et al., 2013; Graham et al., 2015).

Falls Status and Prior Minor Musculoskeletal Injury

Although not one of the main aims of the current study, all 12 participants who reported a minor musculoskeletal injury within the 6 months prior to their involvement in the study experienced a fall during the 12-month prospective fall monitoring period. Furthermore, prior minor injury status was the only variable in the present study that was found to differ between fallers and nonfallers. Prior studies have reported that musculoskeletal conditions such as knee and/or hip osteoarthritis appear to increase falls risk (Khalaj et al., 2014; Smith et al., 2018; Tsonga et al., 2015). As, potential participants who reported having clinically diagnosed lower limb osteoarthritis were excluded from the present study, our findings suggest that arguably more minor musculoskeletal conditions such as soft tissue injury, may be an early warning of elevated falls risk, and suggest further investigation of this possibility is warranted in a more definitive study.

Strengths and Limitations

A strength of the present study was the 12-month prospective evaluation of falls and the direct measurement of PA using activity monitors. The use of actigraphy provides an objective estimate of PA level and is considered the gold standard for activity monitoring. Prospective evaluation of falls provides insight into the temporal relationship between habitual PA, prior injury, and falls. There are also several limitations that should be considered when interpreting the results of this study. First, previous studies have reported older adults spend as little as 10–20 min engaged in moderate- to vigorous-intensity PA per day (Troiano et al., 2008). However, in the present study, the absolute level of PA intensity level observed was low (only activity classified as sedentary and light intensities were observed). Therefore, our findings of PA intensity not being related to prospective falls in older adults cannot be generalized to higher levels of PA intensity. Second, the presence of a prior minor injury was recorded during screening, but the exact nature of the injuries was not recorded for all participants. However, due to the overall inclusion criteria for the study we are certain the injuries were minor in nature. Third, the fall rate observed in this study was relatively low (17%) compared with other prospective fall studies in older adults where rates are typically one in three to four (Klenk et al., 2015; Okubo et al., 2015, 2016). We contend that the low fall rate in the present study may be due to the overall high level of PF of the participants who were free from chronic health conditions. Finally, the sample size of 104 participants, used in the present study may not be fully representative of the population of older adults in the wider community. Therefore, we caution against generalizing the findings of the present study to other populations.

Conclusion

Baseline measures of PA, PF, and strength did not differentiate between fallers and nonfallers in a cohort of 104 highly functioning, largely sedentary community-dwelling older adults. However, all participants who reported a musculoskeletal injury in the 6 months prior to participation in this study experienced at least one fall, which suggests that musculoskeletal injuries (such as soft tissue sprains and strains) may need to be considered as a potential falls risk factor.

Acknowledgments

Research reported in this publication was supported by the Australian National Health and Medical Research Council (project grant 536508) and by the National Institute of General Medical Sciences of the National Institutes of Health under Award Number P20GM103474. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. Whitten was supported by the National Center for Advancing Translational Sciences of the National Institutes of Health under Award Number TL1 TR002318. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

References

Aguilar-Farías, N., Brown, W.J., & Peeters, G.G. (2014). ActiGraph GT3X+ cut-points for identifying sedentary behaviour in older adults in free-living environments. *Journal of Science and Medicine in Sport, 17*(3), 293–299.

older adults: Analyzing the different risks of falling. *Archives of Gerontology and Geriatrics, 60*(1), 45–51. https://doi.org/10.1016/J.ARCHGER.2014.10.008

Podsiadlo, D., & Richardson, S. (1991). The timed "up & go": A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society, 39*(2), 142–148. https://doi.org/10.1111/J.1532-5415.1991.TB01616.X

Rivera-Torres, S., Fahey, T.D., & Rivera, M.A. (2019). Adherence to exercise programs in older adults: Informative report. *Gerontology & Geriatric Medicine, 5,* Article 604. https://doi.org/10.1177/2333721418823604

Salari, N., Darvishi, N., Ahmadipanah, M., Shohaimi, S., & Mohammadi, M. (2022). Global prevalence of falls in the older adults: A comprehensive systematic review and meta-analysis. *Journal of Orthopaedic Surgery and Research, 17*(1), Article 334. https://doi.org/10.1186/S13018-022-03222-1

Sasaki, J.E., Júnior, J.H., Meneguci, J., Tribess, S., Marocolo Júnior, M., Stabelini Neto, A., & Virtuoso Júnior, J.S. (2017). Number of days required for reliably estimating physical activity and sedentary behaviour from accelerometer data in older adults. *Disability and Rehabilitation, 36*(14), 1572–1577. https://doi.org/10.1080/02640414.2017.1403527

Sheehan, R.C., Guerrero, N., Wilson, J.B., Zai, C.Z., Kingsbury, T.D., Tullos, M.L., Acasio, J.C., Mahon, C.E., Miller, E., Hendershot, B.D., Dearth, C.L., Grabiner, M.D., & Kaufman, K.R. (2022). Common fall-risk indicators are not associated with fall prevalence in a high-functioning military population with lower limb trauma. *Clinical Biomechanics, 100,* Article 105774. https://doi.org/10.1016/j.clinbiomech.2022.105774

Sherrington, C., Fairhall, N., Kwok, W., Wallbank, G., Tiedemann, A., Michaleff, Z.A., Ng, C.A.C.M., & Bauman, A. (2020). Evidence on physical activity and falls prevention for people aged 65+ years: Systematic review to inform the WHO guidelines on physical activity and sedentary behaviour. *International Journal of Behavioral Nutrition and Physical Activity, 17*(1), Article 1041. https://doi.org/10.1186/S12966-020-01041-3/FIGURES/3

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. https://doi.org/10.1093/PTJ/80.9.896

Smith, T.O., Higson, E., Pearson, M., & Mansfield, M. (2018). Is there an increased risk of falls and fractures in people with early diagnosed hip and knee osteoarthritis? Data from the Osteoarthritis Initiative. *International Journal of Rheumatic Diseases, 21*(6), 1193–1201. https://doi.org/10.1111/1756-185X.12871

Sun, F., Norman, I.J., & While, A.E. (2013). Physical activity in older people: A systematic review. *BMC Public Health, 13*(1), Article 449. https://doi.org/10.1186/1471-2458-13-449/FIGURES/2

Syddall, H.E., Martin, H.J., Harwood, R.H., Cooper, C., & Aihie Sayer, A. (2009). The SF-36: A simple, effective measure of mobility-disability for epidemiological studies. *The Journal of Nutrition, Health & Aging, 13*(1), 57–62.

Tinetti, M.E., & Kumar, C. (2010). The patient who falls: "It's always a trade-off." *The Journal of the American Medical Association, 303*(3), Article 258. https://doi.org/10.1001/JAMA.2009.2024

Troiano, R.P., Berrigan, D., Dodd, K.W., Mâsse, L.C., Tilert, T., & Mcdowell, M. (2008). Physical activity in the United States measured by accelerometer. *Medicine & Science in Sports & Exercise, 40*(1), 181–188. https://doi.org/10.1249/MSS.0B013E31815A51B3

Tsonga, T., Michalopoulou, M., Malliou, P., Godolias, G., Kapetanakis, S., Gkasdaris, G., & Soucacos, P. (2015). Analyzing the history of falls in patients with severe knee osteoarthritis. *Clinics in Orthopedic Surgery, 7*(4), 449–456. https://doi.org/10.4055/CIOS.2015.7.4.449

CHAPTER THREE

MUSCLE QUALITY AND REACTIVE BALANCE CONTROL IN OLDER AND YOUNGER ADULTS

Contribution of Authors and Co-Authors

Author: Justin Whitten

Contributions: Involved in the initial conception of the study and methodological design. Primarily responsible for data collection and analysis and preparing the initial draft of the manuscript.

Co-Author: Dr. Dawn Tarabochia

Contributions: Involved in the initial conception of the study and methodological design. Oversaw data collection, data analysis, and manuscript preparation

Co-Author: Dr. John Seifert

Contributions: Oversaw manuscript preparation.

Co-Author: Dr. David Graham

Contributions: Involved in the initial conception of the study and methodological design. Oversaw data collection, data analysis, and manuscript preparation

Manuscript Information

J. Whitten, D. Tarabochia, J. Seifert, D. Graham

Status of Manuscript:
☒ Prepared for submission to a peer-reviewed journal
☐ Officially submitted to a peer-reviewed journal
☐ Accepted by a peer-reviewed journal
☐ Published in a peer-reviewed journal

Abstract

While age-related declines in muscle quality contribute to strength and mobility impairments, their role in reactive balance control remains unclear. Identifying muscle quality measures that correlate with balance performance may enhance fall risk screening and intervention strategies for older adults. This study investigated the relationship between lower limb muscle quality and reactive balance control, focusing on Maximum Recoverable Lean Magnitude (MRLM) and modified Choice Stepping Reaction Time (CSRT-M) in both older and younger adults. Eighteen participants (underwent ultrasound assessments of muscle quality and thickness in the biceps femoris (BF), medial gastrocnemius (MG), and vastus lateralis (VL). Reactive balance control was measured using a tether-release perturbation to determine MRLM, and the CSRT-M was used to assess step response latency. Pearson correlations and multiple linear regression models were applied to evaluate the relationships between muscle quality and balance performance. BF muscle quality correlated with MRLM ($r = -0.70$) and CSRT-M ($r = 0.56$), while MG quality was also associated with MRLM ($r = -0.71$). In the combined sample, BF muscle quality independently predicted MRLM ($p < 0.01$, $R^2 = 0.51$) and CSRT-M ($p < 0.01$, $R^2 = 0.35$). In older adults, BF muscle quality did not initially predict MRLM. However, after removing a high-leverage outlier, it became a significant predictor ($\beta = -0.84$, $p = 0.01$, $R^2 = 0.51$). These findings suggest that BF muscle quality may be a key factor in balance recovery for older adults and could serve as a marker for fall risk. The results highlight the potential utility of ultrasound-derived muscle quality assessments in both clinical and performance settings. Future research should examine whether targeted hamstring interventions can improve balance responses and reduce fall risk in aging populations.

Introduction

Falls are a leading cause of severe injury in older adults[1,2], with over 25% of adults over 65 experiencing a fall each year[3]. Falls contribute to high hospitalization rates[4] and significant financial burdens[5], making them a major public health concern [6]. While physical activity and exercise offer broad health benefits, their limitations in preventing falls highlight the need for more targeted interventions[7–9].

Numerous factors contribute to fall risk, including balance impairment, strength deficits, reduced functional capacity, and declining muscle quality[10]. Muscle quality can be assessed using direct and indirect methods. Direct methods include imaging-based techniques such as ultrasound, computed tomography (CT), and magnetic resonance imaging (MRI), which provide insights into muscle composition and structural properties. For example, ultrasound-derived echogenicity reflects the proportion of contractile vs. non-contractile tissue, while CT and MRI can assess cross-sectional area and intramuscular fat infiltration[11,12]. In contrast, indirect methods rely on functional outcomes, such as strength-to-mass ratios, to estimate muscle quality. The Muscle Quality Index, for instance, relates muscle strength to muscle mass, offering an indirect assessment of muscle function[13]. While indirect methods highlight functional capacity, direct imaging methods are more efficient and provide detailed insights into muscle architecture [11,12].

Reactive balance control, the ability to regain balance after an external perturbation, is a critical determinant of fall risk. Carty et al. (2015) demonstrated that reactive stepping behavior during a tether-release balance task was predictive of future falls in older adults [14]. Specifically, older adults with a greater Maximum Recoverable Lean Magnitude (MRLM), the greatest lean angle from which they can recover balance in a single step, were less likely to experience a fall in the following year. Further research from the same group demonstrated that muscle force and power are essential for balance recovery[15] and that hamstring function plays a key role in maintaining stability after a perturbation[16].

While direct assessments of reactive balance control, such as the tether-release method, are effective, they can be time-intensive and physically demanding, limiting their feasibility in clinical and research settings [17]. Despite the established link between lower limb function, balance recovery, and fall risk, identifying simple, non-invasive fall risk markers remains a challenge. Advances in B-mode ultrasound imaging present a promising tool for muscle quality assessment, yet its relationship with reactive balance control remains unexplored. This study aimed to address this gap by examining how ultrasound-derived lower limb muscle quality relates to key reactive balance measures in younger and older adults Specifically, we examined whether muscle quality in the biceps femoris (BF), medial gastrocnemius (MG), and vastus lateralis (VL) was associated with MRLM and modified Choice Stepping Reaction Time (CSRT-M), two measures of reactive balance control.

Methods

Participants

Eighteen participants, 12 older adults (age: 65 ± 4.1 years; height: 1.75 ± 0.096 m; weight: 81 ± 17 kg; 8 female) and six younger adults (age: 25 ± 3.4 years; height: 1.79 ± 0.9 m; weight: 79 ± 12 kg; 3 female), were recruited from the local community via word of mouth. Table 1 provides an overview of participant characteristics. Older adults were eligible if they were between 60 and 85 years old, living independently, and able to walk without assistance for at least 15 minutes. Younger adults were excluded if they were outside the 18–35 age range or unable to walk unassisted for the same duration. All participants were free from severe neurological or musculoskeletal conditions. This study was approved by the Montana State University Institutional Review Board, and written informed consent was obtained from all participants before participation.

Muscle Quality Assessment

Muscle quality was assessed using a Telemed ArtUs Portable Ultrasound (Vilnius, Lithuania) with a 7.5 MHz linear transducer. Images were acquired from the dominant leg at standardized anatomical landmarks for the vastus lateralis (VL), biceps femoris (BF), and medial gastrocnemius (MG). VL images were taken at the midpoint between the greater trochanter and lateral epicondyle with the participant supine. BF images were obtained at the same anatomical midpoint with the participant prone. MG images were taken at a site two-thirds of the distance from the medial epicondyle to the medial malleolus, also in the prone position.

Grayscale analysis was performed using Simple Muscle Architecture Analysis[18] in ImageJ[19,20] to calculate echo intensity values on a 0–255 scale, where lower values indicate better muscle quality. Images were acquired and analyzed by a researcher with over 100 hours of experience in ultrasound imaging and analysis.

Balance Control Assessments

Maximum Recoverable Lean Magnitude. The tether-release balance perturbation protocol followed previously published methods[21]. Participants stood shoulder-width apart and leaned forward while maintaining a flat-footed stance. A linear force transducer (ADInstruments, Dunedin, New Zealand) recorded the load applied by the safety harness attached to an inextensible cable. The cable was released at a randomized interval (2–10 s) after the desired lean force was achieved. Participants were instructed not to anticipate release and to regain balance with a single step. Ground reaction forces were monitored in real-time using AMTI Optima force plates (Watertown, MA), sampling at 1000 Hz. The largest lean magnitude from which participants successfully recovered balance with a single step was recorded as their MRLM.

Figure 1. Example sequence of a participant completing the tether release balance recovery task while kinematic and kinetic data are recorded

<u>Choice Stepping Reaction Time - Modified</u>. The CSRT-M is a valid and reliable measure of stepping ability in older adults[22]. Participants stood on a 6-box testing mat (Figure 2), with two start boxes and four target boxes. At a randomized verbal cue (e.g., “front right” or “side left”), participants stepped into the specified box and then returned to the start. After eight practice trials, participants completed twelve timed trials, and the total completion time was recorded as their CSRT-M score.

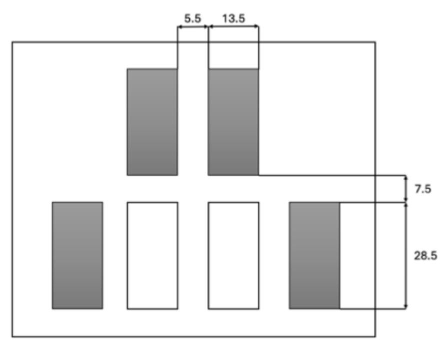

Figure 2. CSRT-M mat. The white boxes are the start boxes, and the gray boxes are the target boxes. Dimensions are in cm.

Statistical Analysis

Descriptive statistics (means ± SDs) were computed for participant demographics, muscle quality, and balance recovery metrics. Analyses of variance (ANOVA) were used to compare age group differences where appropriate. Multiple linear regression models were used to evaluate the predictive value of VL, BF, and MG muscle quality on MRLM and CSRT-M time, both independently and in combination. Older participants unable to complete the MRLM assessment ($n = 2$) were excluded from MRLM-related analyses. A subgroup analysis was conducted to examine these relationships in older adults only. To assess model robustness, diagnostic tests were performed to identify influential data points and potential outliers. Cook's Distance (4/n threshold) was used to identify influential observations, as values exceeding this threshold suggest a disproportionate impact on the model. Leverage values were also assessed, with observations exceeding 2–3 times the average leverage flagged as potential outliers. Model fit was assessed using R^2, and statistical significance was set at $p < 0.05$. All analyses were performed in R Statistical Software (version 4.3.0).

Results

Comparison of Older and Younger Participants

Younger and older participants did not significantly differ in terms of height or weight. However, younger participants exhibited significantly greater muscle quality and thickness in the biceps femoris and medial gastrocnemius compared to their older counterparts. Additionally, younger participants demonstrated a significantly higher MRLM (24° ± 2.1° vs. 18° ± 3.9°, $p < 0.01$) and faster CSRT-M (23 ± 2.8 s vs. 31 ± 8.3 s, $p < 0.01$). Seven of the twelve older participants were classified as being at elevated risk of falling, based on the established CSRT-M cutoff of 30 seconds [22–24].

Correlational analyses across the full sample revealed significant relationships between muscle quality and balance control metrics. BF muscle quality was moderately to strongly correlated with CSRT-M ($r = 0.56$), MRLM ($r = -0.70$), and step execution time during balance recovery ($r = 0.64$). MG muscle quality was also significantly correlated with MRLM ($r = -0.71$). However, vastus lateralis (VL) muscle quality was not notably correlated with any balance control measures.

Multiple linear regression analyses revealed that, among all participants, biceps femoris muscle quality was an independent predictor of MRLM ($p < 0.01$, $R^2 = 0.51$) and CSRT-M ($p < 0.01$, $R^2 = 0.35$), while medial gastrocnemius muscle quality independently predicted MRLM ($p < 0.01$, $R^2 = 0.31$).

Table 1. Participant Characteristics

	Older	Younger	Test
Demographics			
Female (%)	8 (67%)	3 (50%)	na
Age (years)	65 ± 4.1	25 ± 3.4	na
Height (cm)	175 ± 9.6	179 ± 9	F=0.622
Weight (kg)	81 ± 17	79 ± 12	F=0.057
Measures of balance			
CSRT (s)	31 ± 8.3	23 ± 2.8	F=11.918***
CSRT (high risk)	7 (58%)	0	X^2=4.129**
MRLM (º)	18 ± 3.9	24 ± 2.1	F=13.62***
Muscle measures			
Biceps Femoris			
Quality (au)	44 ± 4.6	34 ± 1.7	F=27.138***
Thickness (mm)	24 ± 2.4	27 ± 2.4	F=3.932*
Vastus lateralis			
Quality (au)	39 ± 7.4	34 ± 2.7	F=5.155**
Thickness (mm)	24 ± 3.8	23 ± 2.4	F=0.182
Medial Gastrocnemius			
Quality (au)	45 ± 5	38 ± 1.7	F=10.161***
Thickness (mm)	14 ± 1.8	17 ± 1.8	F=7.201**

Statistical significance markers: * p<0.1; ** p<0.05; *** p<0.01. TUG: timed up and go, CSRT: choice step reaction test, MRLM: maximum recoverable lean magnitude. Muscle quality is reported on a scale from 0-255 arbitrary units where lower values indicate superior quality.

Analysis of older participants

Among older adults, neither BF nor MG muscle quality significantly predicted MRLM or CSRT-M in initial models. However, diagnostic analyses revealed a single influential data point with a Cook's Distance of 2.3 (threshold = 0.36) and a leverage value of 0.49 (threshold = 0.36). Upon removing this outlier, BF muscle quality emerged as a significant predictor of MRLM (β= -0.84, t = -4.16, p = 0.01, R2 = 0.51), suggesting that higher BF muscle quality may contribute to improved balance recovery capacity in older adults

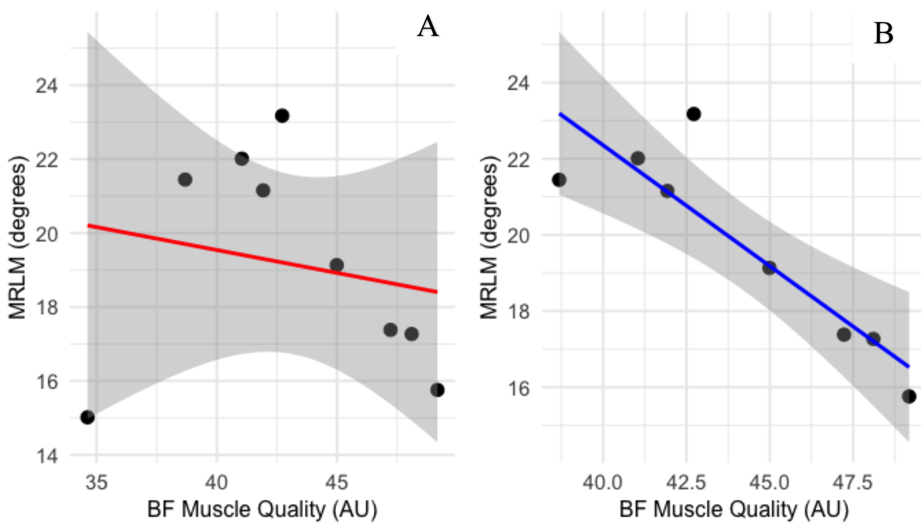

Figure 3. Biceps femoris muscle quality (arbitrary units) vs Maximum Recoverable Lean Magnitude (degrees), Figure 3A includes the outlier, and figure 3B depicts the relationship with the outlier removed.

This study examined the relationship between lower-limb muscle quality and reactive balance control in younger and older adults, with a specific focus on the biceps femoris (BF), vastus lateralis (VL), and medial gastrocnemius (MG). As expected, significant differences in muscle quality and balance performance were observed between age groups. More importantly, biceps femoris muscle quality was strongly associated with maximum recoverable lean magnitude (MRLM) and choice stepping reaction time-modified (CSRT-M). In older adults specifically, BF muscle quality became a significant predictor of MRLM after removing a single influential data point. These findings suggest that muscle quality, particularly in the biceps femoris, may play a critical role in balance recovery and fall risk reduction in aging populations.

Muscle Quality and Balance Control

Consistent with previous research, younger participants exhibited significantly higher muscle quality in both the biceps femoris and medial gastrocnemius compared to their older counterparts. Age-related declines in muscle quality are largely attributed to increased intramuscular fat infiltration, reductions in contractile tissue, and impaired neuromuscular function[25–27]. While younger participants also had greater muscle thickness, the observed correlations suggest that muscle quality, rather than strength or cross-sectional area, could be a stronger determinant of balance performance. This aligns with prior findings indicating that muscular power and neuromuscular efficiency are more relevant to fall prevention than muscle mass alone[15].

In the full sample, BF muscle quality was significantly correlated with both MRLM (r = -0.70) and CSRT-M (r = 0.56). The negative correlation between BF muscle quality and MRLM suggests that individuals with lower muscle quality have a reduced capacity for balance recovery. This is particularly relevant given that lower MRLM values are associated with increased fall risk[14]. Similarly, the positive correlation between BF muscle quality and CSRT-M suggests that poorer BF muscle quality may be linked to longer reaction times for initiating a reactive step. Notably, MG muscle quality was also correlated with MRLM (r = -0.71) but did not predict CSRT-M, suggesting that the BF may play a greater role in balance recovery step execution.

The Predictive Value of Muscle Quality in Older Adults

Among older adults, initial regression models did not identify a significant relationship between muscle quality and balance control metrics. However, after identifying and removing a single influential data point with high Cook's Distance (2.3) and leverage (0.49), BF muscle quality became a significant predictor of MRLM ($\beta = -0.84$, $t = -4.16$, $p = 0.01$, $R^2 = 0.51$). This finding suggests that, despite interindividual variability, muscle quality in the BF may play a key role in balance recovery for older adults. The predictive strength of BF muscle quality for MRLM further reinforces its role in dynamic stability and the ability to control the trunk during balance recovery. These results align with prior studies demonstrating that age-related declines in lower-limb muscle function contribute to impaired balance control[28–30].

Practical Implications

The findings of this study have several implications for fall prevention strategies in older adults. First, ultrasound-derived measures of muscle quality may be valuable as a non-invasive screening tool for identifying individuals at greater risk of balance deficits. If validated in larger samples, biceps femoris muscle quality assessments could help guide targeted interventions aimed at improving reactive balance control.

Additionally, these results highlight the importance of incorporating comprehensive lower limb training, including comprehensive and reactive hamstring training in fall prevention programs. Given the biceps femoris' role in decelerating forward momentum and facilitating rapid stepping responses, exercises that improve neuromuscular function in this muscle group, such as eccentric hamstring training, reactive stepping drills, and perturbation-based balance training, may enhance dynamic stability in older adults. Future studies should explore whether improvements in biceps femoris muscle quality translate to better reactive stepping ability and reduced fall risk.

Considerations and Future Directions

Several limitations should be acknowledged when interpreting these findings. The small sample size and homogeneity of participants limit the generalizability of the regression models, particularly in the older adult subset. As such, caution should be exercised when applying these results to broader aging populations. Additionally, while ultrasound imaging provides a reliable measure of muscle quality, it does not directly assess neuromuscular activation patterns during balance tasks. Future studies should replicate these findings in larger, more diverse samples, including individuals with varying functional capacities, and integrate electromyography and biomechanical analyses to further understand the mechanisms linking muscle quality to reactive stepping performance. While biceps femoris muscle quality emerged as a strong predictor of MRLM after outlier removal, further research is needed to confirm this finding in larger, more diverse cohorts. Longitudinal studies should also investigate whether age-related declines in BF muscle quality predict increased fall risk over time.

Conclusion

This study provides preliminary evidence that biceps femoris muscle quality may be linked to reactive balance control in older adults. After adjusting for a single influential data point, BF muscle quality emerged as a significant predictor of MRLM, suggesting a potential role in dynamic stability and fall risk. While promising, further research is needed to confirm its relevance in aging populations.

References

1. Hayes, W. C. *et al.* Impact near the hip dominates fracture risk in elderly nursing home residents who fall. *Calcif Tissue Int* **52**, 192–198 (1993).

2. Jager, T. E., Weiss, H. B., Coben, J. H. & Pepe, P. E. Traumatic brain injuries evaluated in U.S. emergency departments, 1992- 1994. *Academic Emergency Medicine* **7**, 134–140 (2000).

3. Bergen, G., Stevens, M. R. & Burns, E. R. Falls and Fall Injuries Among Adults Aged ≥65 Years — United States, 2014. *MMWR Morb Mortal Wkly Rep* **65**, 993–998 (2016).

4. Australian Institute of Health and Welfare. Injury in Australia. *Falls* https://www.aihw.gov.au/reports/injury/falls#More%20info (2022).

5. Hoffman, G. *et al.* Incidence of and County Variation in Fall Injuries in US Residents Aged 65 Years or Older, 2016-2019. *JAMA Netw Open* **5**, e2148007–e2148007 (2022).

6. James, S. L. *et al.* The global burden of falls: global, regional and national estimates of morbidity and mortality from the Global Burden of Disease Study 2017. *Injury Prevention* **26**, i3–i11 (2020).

7. McCrum, C. *et al.* Perturbation-based balance training: Principles, mechanisms and I implementation in clinical practice. *Front Sports Act Living* **4**, (2022).

8. Sherrington, C. *et al.* Evidence on physical activity and falls prevention for people aged 65+ years: systematic review to inform the WHO guidelines on physical activity and sedentary behaviour. *International Journal of Behavioral Nutrition and Physical Activity* **17**, 1–9 (2020).

9. Whitten, J. *et al.* Baseline Measures of Physical Activity and Function Do Not Predict Future Fall Incidence in Sedentary Older Adults: A Prospective Cohort Study. *J Aging Phys Act* **32**, 207–212 (2023).

10. Tinetti, M. E. & Kumar, C. The Patient Who Falls: "It's Always a Trade-off". *JAMA : the journal of the American Medical Association* **303**, 258 (2010).

11. Stock, M. S. & Thompson, B. J. Echo intensity as an indicator of skeletal muscle quality: applications, methodology, and future directions. *Eur J Appl Physiol* **121**, 369–380 (2021).

12. Franchi, M. V. *et al.* Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques. *Ultrasound in Medicine and Biology* vol. 44 2492–2504 Preprint at https://doi.org/10.1016/j.ultrasmedbio.2018.07.010 (2018).

13. Barbat-Artigas, S., Rolland, Y., Zamboni, M. & Aubertin-Leheudre, M. How to assess functional status: A new muscle quality index. *J Nutr Health Aging* **16**, 67–77 (2012).

14. Carty, C. P. *et al.* Reactive stepping behaviour in response to forward loss of balance predicts future falls in community-dwelling older adults. *Age Ageing* **44**, 109–115 (2015).

15. Graham, D. F., Carty, C. P., Lloyd, D. G. & Barrett, R. S. Biomechanical predictors of maximal balance recovery performance amongst community-dwelling older adults. *Exp Gerontol* **66**, 39–46 (2015).

16. Graham, D. F., Carty, C. P., Lloyd, D. G., Lichtwark, G. A. & Barrett, R. S. Muscle contributions to recovery from forward loss of balance by stepping. *J Biomech* (2014) doi:10.1016/j.jbiomech.2013.11.047.

17. Whitten, J. *et al.* The Acceptability of a Community-Based Perturbation-Based Balance Training to Older Adults and Healthcare Professionals. *Gerontol Geriatr Med* **10**, (2024).

18. Seynnes, O. R. & Cronin, N. J. Simple Muscle Architecture Analysis (SMA): An ImageJ macro tool to automate measurements in B-mode ultrasound scans. *PLoS One* **15**, e0229034 (2020).

19. Schneider, C. A., Rasband, W. S. & Eliceiri, K. W. NIH Image to ImageJ: 25 years of image analysis. *Nature Methods 2012 9:7* **9**, 671–675 (2012).

20. Rueden, C. T. *et al.* ImageJ2: ImageJ for the next generation of scientific image data. *BMC Bioinformatics* **18**, 1–26 (2017).

21. Carty, C. P., Mills, P. & Barrett, R. Recovery from forward loss of balance in young and older adults using the stepping strategy. *Gait Posture* (2011) doi:10.1016/j.gaitpost.2010.11.017.

22. Delbaere, K. *et al.* Validity and reliability of a simple 'low-tech' test for measuring choice stepping reaction time in older people Article. *Clin Rehabil* **30**, 1128–1135 (2016).

23. Tijsma, M., Vister, E., Hoang, P. & Lord, S. R. A simple test of choice stepping reaction time for assessing fall risk in people with multiple sclerosis. *Disabil Rehabil* **39**, 601–607 (2017).

24. St George, R. J., Fitzpatrick, R. C., Rogers, M. W. & Lord, S. R. Choice Stepping Response and Transfer Times: Effects of Age, Fall Risk, and Secondary Tasks. *The Journals of Gerontology: Series A* **62**, 537–542 (2007).

25. Watanabe, Y., Ikenaga, M., Yoshimura, E., Yamada, Y. & Kimura, M. Association between echo intensity and attenuation of skeletal muscle in young and older adults: A comparison between ultrasonography and computed tomography. *Clin Interv Aging* **13**, 1871–1878 (2018).

26. Goodpaster, B. H. *et al.* Attenuation of skeletal muscle and strength in the elderly: The health ABC study. *J Appl Physiol* **90**, 2157–2165 (2001).

27. Kent-Braun, J. A., Ng, A. V. & Young, K. Skeletal muscle contractile and noncontractile components in young and older women and men. *J Appl Physiol* **88**, 662–668 (2000).

28. Menant, J. C., Steele, J. R., Menz, H. B., Munro, B. J. & Lord, S. R. Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people. *Gait Posture* **29**, 392–397 (2009).

29. Kim, H. K. & Chou, L. S. Lower limb muscle activation in response to balance-perturbed tasks during walking in older adults: A systematic review. *Gait Posture* **93**, 166–176 (2022).

30. Daubney, M. E. & Culham, E. G. Lower-Extremity Muscle Force and Balance Performance in Adults Aged 65 Years and Older. *Phys Ther* **79**, 1177–1185 (1999).

CHAPTER FOUR

THE ACCEPTABILITY OF COMMUNITY-BASED PERTURBATION-BASED BALANCE TRAINING TO OLDER ADULTS AND HEALTHCARE PROFESSIONALS

Contribution of Authors and Co-Authors

Author: Justin Whitten

Contributions: Involved in the initial conception of the study and methodological design. Primarily responsible for data collection and analysis and preparing the manuscript.

Co-Author: Bryant O'Leary

Contributions: Instrumental in data collection and analysis.

Co-Author: Dr. David Graham

Contributions: Involved in the initial conception of the study and methodological design.

Co-Author: Dr. Michelle Grocke-Dewey

Contributions: Involved in the initial conception of the study and methodological design. Oversaw data collection, data analysis, and manuscript preparation

Co-Author: Julie Riley

Contributions: Involved in data collection, participant recruitment, and logistical management of the community aspect.

Co-Author: Danielle Harper

Contributions: Involved in data collection, participant recruitment, and logistical management of the community aspect.

Co-Author: Dr. Dawn Tarabochia

Contributions: Involved in the initial conception of the study and methodological design. Oversaw data collection, data analysis, and manuscript preparation

Manuscript Information

J. Whitten, B. O'Leary, D. Graham, M. Grocke-Dewey, J. Riley, D. Harper, D. Tarabochia

Status of Manuscript:
☐ Prepared for submission to a peer-reviewed journal
☐ Officially submitted to a peer-reviewed journal
☐ Accepted by a peer-reviewed journal
☒ Published in a peer-reviewed journal

Gerontology & Geriatric Medicine
April 15, 2024
Volume 10, 2024
DOI: https://doi.org/10.1177/23337214241246843

Article

Gerontology & Geriatric Medicine
Volume 10: 1–13

DOI: 10.1177/23337214241246843
journals.sagepub.com/home/ggm
Sage

The Acceptability of a Community-Based Perturbation-Based Balance Training to Older Adults and Healthcare Professionals

Justin Whitten, MS[1,2,3], Bryant O'Leary, MS[1], David Graham, PhD[1,3], Michelle Grocke-Dewey, PhD[1], Julie Riley, MBA[1], Danielle Harper, BS[1], and Dawn Tarabochia, PhD[1]

Abstract

Background: Perturbation-based balance training (PBT) is a promising fall risk reduction method that involves inducing unexpected perturbations to balance to train participants reactive balance control. Due to the unpredictable nature of PBT, its acceptability to older adults could present a barrier to the implementation of PBT in the community. **Aim/Purpose:** The purpose of this study was to assess the perceived acceptability of a community-based PBT program to both older adults and healthcare professionals (HCPs). **Methods:** Nineteen older adults (aged 69.6 ± 6.6 years, 17 women, 2 men) and three HCPs participated in the qualitative study. Participants completed four PBT sessions facilitated in conjunction with HCPs. Interviews, based on the theoretical framework of acceptability, were conducted before and after PBT and analyzed using template analysis. **Results:** PBT was perceived as effective by older adults and HCPs. However, HCPs perceived the equipment cost as a substantial barrier to feasibility in the community.

Keywords

perturbation-based balance training, acceptability, balance, community-based

Manuscript received: August 31, 2023; **final revision received:** March 13, 2024; **accepted:** March 24, 2024.

What This Paper Adds

- To our knowledge, this is the first study to evaluate:
  - the acceptability of PBT from multiple temporal perspectives;
  - the perceptions of both older adults and healthcare professionals simultaneously.
- The community setting of the present study provides insights into perceived barriers and facilitators in a different light than previous investigations conducted in the laboratory.

Applications of Study Findings

- PBT fall prevention programs were acceptable to both older adults and HCPs in a rural community.
- The type of equipment used to implement PBT may influence perceived acceptability.
- There is a need for PBT modalities that can be more feasibly implemented in a community setting.

Introduction

Falls are a leading cause of morbidity and mortality in older adults (Bergen et al., 2016). Conventional Balance Training (CBT) programs, which are typically exercise-based and may target both strength and balance, have been demonstrated to reduce falls to an extent (Sherrington et al., 2020). However, CBT targets static and proactive balance control (Huxham et al., 2001) and requires a relatively large training dose to elicit protective effects against falls while the

[1]Montana State University, Bozeman, USA
[2]Institute of Translational Health Sciences, Seattle, USA
[3]Griffith University, Gold Coast, Queensland, Australia

Corresponding Author:
Justin Whitten, Department of Food Systems, Nutrition and Kinesiology, Montana State University, Bozeman, Montana, PO Box 173540, Bozeman, MT 59717-3540, USA.
Email: justinwhitten@montana.edu

Table 1. Theoretical Framework of Acceptability.

Acceptability	A multi-faceted construct that reflects the extent to which people delivering or receiving a healthcare intervention consider it to be appropriate, based on anticipated or experiential cognitive and emotional responses to the intervention	
Components of acceptability:		
	Affective attitude	How an individual feels about the intervention
	Burden	The perceived amount of effort that is required to participate in the intervention
	Ethicality	The extent to which the intervention is a good fit with an individual's value system
	Intervention coherence	The extent to which the participant understands the intervention and how it works
	Opportunity costs	The extent to which benefits, profits, or values must be given up to engage in the intervention
	Perceived effectiveness	The extent to which the intervention is perceived as likely to achieve its purpose
	Self-efficacy	The participant's confidence that they can perform the behavior(s) required to participate in the intervention

Source. Adapted from Sekhon et al. (2017).

retention of these effects appears to be dependent on continued participation (Sherrington et al., 2020). CBT programs are primarily comprised of predictable and volitional quasistatic tasks (Burns et al., 2023). Yet, most older adults fall because of unexpected losses of balance such as slips, trips, or stumbles (Blake et al., 1988; Luukinen et al., 2000; Talbot et al., 2005). As such, CBT appears to have insufficient task specificity to efficiently minimize fall risk in older adults.

Perturbation Balance Training (PBT) is a balance training paradigm that has garnered increased interest since the early 2000s due to its task-specific nature and its potential to effectively reduce fall risk in older adults (Devasahayam et al., 2022). Briefly, the goal of PBT is to improve participants' reactive balance control (i.e., the ability to recover from unexpected balance disruptions such as slips, trips, or stumbles). PBT targets reactive balance by repeatedly delivering unexpected perturbations to balance in a safe environment. For a detailed description of PBT, we recommend McCrum et al. (2022). Early reports on PBT indicated it may be highly effective for preventing falls in older adults and required a substantially lower training dose than CBT (Pai et al., 2010; Sherrington et al., 2020). However, more recent findings have been conflicting, and further research is required to fully understand the dose-response relationship for PBT (Gerards et al., 2023). Therefore, researchers and practitioners are gaining interest in PBT as a means to improve reactive balance and mitigate the negative outcomes of a fall for older adults. There are, however, still many considerations to be addressed before PBT can be effectively implemented on a meaningful level. These include understanding the relative efficacy of the different methods of PBT, equipment requirements, and identifying barriers and facilitators to implementing PBT in both clinical and community settings (McCrum et al., 2022).

Surveys of healthcare professionals (HCPs) regarding PBT have identified a lack of knowledge of PBT and the perception that large expensive equipment is necessary for PBT as some of the primary barriers to implementing PBT in clinical practice (Mansfield, Danells, et al., 2021; Margalit et al., 2023). Acceptability can be either a facilitator or barrier to the implementation of any health care intervention. The acceptability of an intervention could influence participant adherence (Hommel et al., 2013; McCrum et al., 2022) or the way HCPs deliver the intervention. For instance, interventions considered less acceptable by HCPs may be delivered with a lower level of fidelity, which can in turn impact the efficacy of the intervention (Borrelli et al., 2005). The Theoretical Framework of Acceptability (TFA) (Sekhon et al., 2017), proposes that the acceptability of a healthcare intervention is a multidimensional construct with seven components (Affective Attitude, Burden, Ethicality, Intervention Coherence, Opportunity Costs, Perceived Effectiveness, and Self-efficacy) that can be assessed prospectively, concurrently, and retrospectively. Please refer to Table 1 for a description of the seven TFA components.

Until recently, evidence regarding the acceptability of PBT to older adults has been limited to indirect measures such as training adherence, adverse events, and dropout rates reported by previous studies (Mansfield et al., 2010; Okubo, Sturnieks, et al., 2019). Recently, Gerards et al. (2022) utilized the TFA to describe the acceptability of PBT to older adults with a history of recent falls. To our knowledge, the study by Gerards et al. was the first and only direct investigation of the acceptability of PBT, the authors reported that PBT was perceived to be acceptable by older adults. The novelty of PBT and the improved self-efficacy and balance confidence were identified as facilitators of perceived acceptability. The authors also noted several limitations to their study including the retrospective design which makes it difficult to determine how participants' perceptions of PBT changed throughout the intervention. Additionally, the analysis by Gerards et al. (2022) was conducted as part of a larger trial set in a university hospital and therefore the results may not be generalizable to PBT interventions delivered in community settings. Finally, while Gerards et al. investigated the perceived acceptability of PBT to older adults, they did not

Figure 1. PBT treadmill.

consider the acceptability of practitioners delivering the intervention which may be an equally important consideration, according to the authors of the TFA Sekhon et al. (2017).

To our knowledge, no studies have directly assessed the acceptability of PBT to both the older adults participating in the training and the HCPs delivering the training. Therefore, the purpose of this study was to assess the perceived acceptability of a community-based PBT program to both older adult participants and local HCPs.

Methods

Context

To maintain a community perspective while conducting PBT within a research project, the present study was codesigned with members of the Cooperative Extension System (CES). The CES is affiliated with land grant universities in each state in the US and has offices in most of the nation's counties (*Extension | National Institute of Food and Agriculture*, 2022). Extension agents in each county offer community members access to research-based programs ranging from financial education to health promotion which make them ideal candidates for implementing community-based programs, including ones on fall prevention. The PBT program was advertised by local extension programs in rural communities and the PBT intervention was delivered at the local community center, as is common with programs delivered through the CES. Refer to Figure 1 for an idea of the training setting. Extension agents also recruited local HCPs working in the rural communities to deliver the PBT intervention.

PBT Protocol

The PBT intervention protocol consisted of four 30 to 45-min sessions over 4 weeks (one session per week). Perturbations were delivered using a custom dual belt treadmill capable of producing perturbations similar to those previously reported (Gerards et al., 2021; Grabiner et al., 2008). Participants wore a safety harness at all times when on the treadmill. After a brief warmup, older adults were exposed to postural and gait perturbations which were delivered via unexpected changes in direction and velocity of the treadmill belts. Treadmill belt acceleration profiles (i.e., perturbation intensity) were selected based on previously published PBT protocols (Gerards et al., 2021; Wang et al., 2019). Participants experienced 20 to 45 perturbations per session. Perturbation intensity and volume were progressed on an individual basis throughout the protocol and generally increased throughout the protocol.

Participants

Nineteen community-dwelling (i.e., living independently in the community) older adults (60–85 years) were recruited from a rural area using convenience and purposive sampling. Older adults were eligible if they were community-dwelling and able to walk without an assistive device. Exclusion criteria included risk factors that may have influenced the safety of training such as osteoporosis, recent injuries to the lower extremities such as fractures or major strains, a score of 23 or less on the Mini-Mental State Examination (Tombaugh & McIntyre, 1992), or the use of medications known to impair balance. Three HCPs were also recruited from the local area by extension agents to deliver the PBT program in the rural community setting, which accounted for approximately 70% of available HCPs within the communities.

Data Collection Procedures

The TFA is a framework designed specifically to assess participant and HCP perceptions of acceptability in the evaluation of the implementation and outcomes of programs specific to improving health outcomes (Sekhon et al., 2017). Thus, the development of the interview questions was based on the TFA (Sekhon et al., 2017); semi-structured interviews were used to assess the prospective and retrospective perceived acceptability of PBT to older adults and local HCPs. Each construct within the TFA was operationalized into corresponding, semi-structured interview questions per the previous investigation conducted by Gerards et al. (2022). Table 2 provides a list of example interview questions and corresponding constructs. As in Gerards et al., questions regarding context-specific considerations such as training location and training individually as opposed to in a

Table 2. TFA Components, Interpretations and Related Questions.

Theme	Interpretation and related questions
Affective attitude	Interpretation—How an individual feels about PBT HCP: How appropriate do you feel PBT was for your community members/How do you feel facilitating PBT affected your other programs OA: Now that the details of the PBT program have been explained to you, can you tell me how you feel about participating in the training?
Burden	Interpretation—The perceived amount of effort that is required to participate in or deliver PBT HCP: Were there any aspects of implementing PBT that you feel affected your ability to facilitate other programs or execute other aspects of your job? Either positive or negative OA: To what extent do you expect the training to be difficult?
Ethicality	Interpretation—The extent to which the intervention has a good fit within an individual's value system HCP: How appropriate do you feel PBT was for your community members OA: To what extent does PBT fit with your views on fall prevention?
Intervention coherence	Interpretation—The extent to which the participant understands the goal of PBT and how it works HCP: Not addressed for HCPs since all were familiar with PBT before the intervention OA: Can you explain to me what the goal of the training is?
Opportunity cost	Interpretation—The extent to which benefits, profits or values must be given up to participate in or deliver PBT HCP: What costs (if any) did facilitating PBT incur on you or your other programs OA: To what extent do you anticipate having to give up other activities or things you value to participate in PBT?
Perceived effectiveness	Interpretation—The extent to which the participants perceived PBT to be effective HCP: Did you observe any positive or negative effects of participation in PBT on the participants/ Do you feel that the PBT program was implemented successfully OA: To what extent do you think the training will be a benefit to your recreational or occupational activities?
Self-efficacy	Interpretation—The participants are confident that they can perform PBT HCP: To what extent do you feel capable of continuing to offer PBT/How efficiently do you feel the PBT program was implemented OA: How do you feel you will do during PBT?

group setting were added to understand their potential impact on the perceived acceptability of PBT.

Interviews were conducted at a local community center. All participants (older adults and HCPs) were interviewed twice, prospective interviews were conducted 1 week before PBT and the retrospective interviews were conducted 1 week after PBT. Interviews lasted approximately 10 min and were conducted between August and September 2022. Interviews were primarily conducted by DT, a gerontologist with extensive experience conducting interviews and qualitative research. DT was not involved in delivering the PBT program but was familiar with PBT such that she was able to ask relevant individualized follow-up questions. The interview guide was updated iteratively to account for the emergence of new themes. All interviews were recorded using a digital voice recorder and transcribed verbatim. A second researcher was always present as an observer during interviews and training sessions to take field notes for triangulation.

Analytical Procedures. This study utilized a qualitative method known as template analysis to analyze data from the prospective and retrospective interviews. Template analysis is a type of thematic analysis which is a broad category of qualitative approaches used to develop themes from textual data (Brooks et al., 2015). Template analysis allows for flexible, hierarchical coding and is an effective method when using a priori themes within an analysis. In template analysis, researchers construct an initial template for coding data utilizing a priori themes. A subset of the data is reviewed, and the template is modified to include any emerging themes. A second subset of the data is then reviewed, and if needed, the template is modified. The review of the data and subsequent modification of the template occurs until the researchers reach a consensus that all themes are represented on the template (Brooks et al., 2015).

Coding. The original template utilized a priori themes, based on the TFA and results from Gerards et al. (2022). Using a similar process to Gerards et al. (2022), prospective and retrospective interviews and field notes for four transcripts were coded independently by DT and JW. Researchers discussed the codes until a consensus was reached and the template was updated accordingly. This process was repeated for the next four transcripts and the template was adjusted. For the third iteration of the process, another four transcripts were reviewed.

Consensus was reached between the researchers and the template was deemed complete. A total of 12 transcripts were reviewed during this reiterative process. JW coded the remaining transcripts independently. Coding was conducted using NVivo version 1.7.1.

Triangulation and Reflexivity. For triangulation, an independent researcher who had not been involved in data collection or analysis thus far (MG) independently coded all interviews using the final template. All three researchers (JW, DT, and MG) discussed the codes, and consensus was reached that the final version of the template encompassed all themes present in the interviews and that coding saturation was reached. Notably, due to logistical constraints, DT was unable to conduct pre-training interviews for six participants. JW, who was involved in the PBT intervention conducted interviews for these participants. Coding the interviews by JW revealed no new themes, which can be considered secondary confirmation of saturation.

Table 3. Participant Characteristics.

Participant	Sex	Age (years)	Interviewer (pre/post PBT)
P02	Female	81	DT
P04	Female	68	DT
P05	Female	70	DT
P07	Female	75	DT
P08	Male	65	DT
P11	Female	79	DT
P14	Female	66	DT
P15	Female	64	DT
P17	Female	84	DT
P20	Female	74	DT
P22	Female	75	DT
P24	Female	66	DT
P25	Female	70	DT
P26	Female	61	DT
P30	Female	61	DT/JW
P31	Female	70	DT/JW
P32	Male	63	DT/JW
P33	Female	63	DT/JW
P34	Female	68	DT/JW

Results

Participants

A convenience sample of 19 older adults (17 women and 2 men, average age 69.6 ± 6.6 years) across three communities completed the study. For reference, 28 older adults were approached but several were excluded due to medication ($n=5$), cognitive impairment ($n=1$), and the presence of chronic health conditions ($n=3$). Two participants dropped out due to illness not related to training. Three participants missed one session due to scheduling conflicts. One participant elected to drop out of the study during their second training session due to fear of falling. Refer to Table 3 for an overview of participant characteristics. Overall training adherence was 93% for study participants. Three local HCPs (two physical therapists and an occupational therapist) were approached and agreed to participate in the study. Ethics approval was obtained from the Montana State University Institutional Review Board and all participants provided written informed consent before participation. Please refer to Table 4 for a summary of results organized by TFA theme.

Acceptability

Findings from interviews with older adults and HCPs are presented within the seven components of the TFA. If temporal differences in perceived acceptability were found for a given construct, they are reported under the associated construct.

Affective Attitude

Older Adults. The prospective affective attitude was high amongst older adults in this study. Most older adults reported that they would be able to complete the training without too many difficulties, and the benefits of the training would outweigh any difficulties. When asked about how well they would do in the training, one older adult stated,

> Oh, I think I'll do fine. I feel that I'm physically fit enough. . .To be able to learn and be able to do it. (P04)

After completion of the PBT program most older adults indicated it was a positive experience and that they would participate in PBT again.

> It built my confidence (. . .) and it reassured me that if I trip, chances are I'm not going to fall, I'll catch myself. And I like that. (P14)

Most participants reported they typically exercised in a group setting and tended to prefer group environments for conventional exercise. However, the individual nature of the PBT program was not identified as a barrier by any participants and several reported that they preferred the individual nature of the PBT program.

> I'm used to doing more group things, group activities, I could see that this does need to be more individualized and yeah, I appreciate the opportunity to have that. (P20)

A few described the potential embarrassment from an unsuccessful balance recovery attempt as a contributing factor to their preference for training individually.

> It was kinda nice to just be individual, so it'd be less embarrassing if you did crash and burn. Only they don't let you crash and so. . . But still. (P24)

Table 4. Summary of Findings.

Theme	Interpretation and related questions
Affective attitude	HCP: Generally, HCPs maintained a positive affective attitude in both prospective and retrospective interviews.
	OA: Some initial apprehension was reported, but this generally dissipated as the PBT program progressed. Overall older adults maintained a positive affective attitude toward the PBT program.
Burden	HCP: The physical and logistical burden of facilitating PBT was perceived as acceptable however the financial burden of acquiring PBT equipment was perceived as a substantial barrier.
	OA: Prospective perceptions of burden were split between those who believed PBT would be challenging and those who thought it would be easy or did not have an opinion. In retrospect, many older adults reported the burden of PBT to be acceptable.
Ethicality	HCP: All HCPs reported that PBT fit within their views on fall prevention and was appropriate for older adults in their community.
	OA: Almost all older adults perceived PBT as a good fit within their views on health and fall prevention both prospectively and retrospectively.
Intervention coherence	HCP: All HCPs were familiar with the general concept of PBT before the intervention and received training on PBT delivery.
	OA: All older adults were able to communicate the general purpose of PBT before the program and many displayed a full understanding of PBT during retrospective interviews.
Opportunity costs	HCP: Overall HCPs perceived the opportunity cost of PBT as acceptable with time being reported as the only cost.
	OA: No older adults reported having to give up any activities, either directly or indirectly, to participate in PBT.
Perceived effectiveness	HCP: Prospective and retrospective perceived effectiveness of PBT was high for HCPs.
	OA: Prospectively many older adults expected PBT to be effective, and retrospectively many older adults described perceived positive effects resulting from PBT.
Self-efficacy	HCP: All HCPs reported that they perceived themselves capable of implementing PBT on their own, provided they had access to proper equipment.
	OA: Most older adults perceived gains in self-efficacy throughout the PBT program.

Several reported initial apprehensions regarding the PBT treadmill and fall arrest system. These participants described their hesitancy stemmed primarily from differences between the PBT treadmill and typical commercial treadmills, specifically the split belt and lack of a control panel and handrails.

> Oh. I didn't like the way it was split. . . 'cause I didn't know to straddle it (. . .) that made me feel unsure. (P14)

> Well, first you go, "Well, where's the handrail?" [chuckle] And then when you realize that's not part of the deal. . . (P32)

However, these differences were not identified as barriers. Rather, some perceived the novelty of the equipment as a facilitator.

> That's a pretty cool setup they got there. I had no idea. I figured it'd be just a simple treadmill, not something kind of high tech (. . .) It's pretty interesting. It looks pretty cool. It's not anything like I expected. (P32)

HCPs. Overall, HCPs maintained a positive affective attitude toward delivering PBT in both the prospective and retrospective interviews. One HCP described how she felt positive about the impact PBT would have on older adults in the local community.

> I think it's gonna be very appropriate and very good. (. . .) So, I'm super-excited to see how much [PBT] does help them (. . .) to see improvement and that's what I'm hoping. (C02)

While all HCPs viewed PBT positively, one noted concern regarding participants' comfort during PBT and fear of falling as potential barriers to participation.

> It will be interesting to see how their comfortability, if that limits them at all (. . .) I just think that can be a barrier. The fear of falling will probably be the biggest barrier, I think. (C02)

However, her concerns were attenuated after delivering the PBT program and the safety equipment was identified as a facilitator of her positive effect toward PBT.

> I think it's definitely appropriate and I think it would be easy to implement, especially with the harness. It makes it safe for anybody to participate. (C02)

Several HCPs expressed that the translational community-based aspect was a facilitator.

> I think it's a great opportunity to see what these programs might look like in a real-life (. . .). And really just trying to improve clinic care out of research. (C01)

Burden

Older Adults. Most agreed that the burden associated with the difficulty of the PBT protocol was acceptable. Prospective to the PBT program, participants were split between those who indicated they thought the training would be challenging and those who believed the training would be easy or did not have an opinion on how challenging the training would be.

> Yes. Some of the balance stuff I'm sure will be [challenging]. I feel like sometimes my balance isn't as good as it used to be. Yeah (P25)

> I have no idea. I'm going into this open-minded. (P32)

One participant, who elected to discontinue training during the second session, cited the difficulty of recovering from perturbations and fear of falling as barriers to her continued participation.

> I just had to grab on, because I felt very insecure (. . .) Mentally, I just couldn't do it (. . .) It was just the treadmill, when [it] stopped that's what got to me. (P07)

Retrospectively, most older adults stated that the level of difficulty was acceptable. One older adult did indicate in the retrospective interview that she perceived the difficulty of PBT as unacceptable due to her fear of falling and cited the fact that the program was being administered as part of a research study as the only reason she completed the program. However, all others agreed that while the training was acceptably challenging and pushed them to their limits, it was not so difficult that it pushed them past their limits. The goal of PBT is to effectively challenge participants about the velocity and number of perturbations but not to exceed their capacity to recover.

> If it went super-fast, it could have been challenging, but it wasn't, (. . .) I mean, they went to my limit, but they didn't go over my limit. (P11)

HCPs. Prospectively, HCPs indicated that PBT would be something that could be done at their clinics with little burden. When asked if PBT would be something that could be successful in their community, one HCP stated,

> If the set-up was available, [it would be] super easy. (C04)

Retrospectively, the physical burden of delivering PBT was perceived as acceptable and easy to implement (assuming access to proper equipment) by all HCPs. The ease of use and scalability of perturbation magnitude afforded by the treadmill were cited as facilitators.

> It seems very easy to implement, just like any other protocol that would be lined out, easy to adjust, easy to scale. (C01)

One HCP identified the compatibility with practices that are already in place at her clinic as a facilitator.

> It would probably work well with what my job is, as I work in the [local occupational therapy clinic] (. . .) It would actually go really nicely with what I do with the elderly folks over there. (C04)

All HCPs agreed, however, that they did not feel confident in their ability to obtain a PBT treadmill independent of the research project, citing the cost of the PBT treadmill as the sole/primary barrier to implementation.

> Financial [barriers] would be the only thing I could see. (C01)

Cost was identified as a barrier during both pre- and post-PBT interviews.

> Like the split treadmill is not gonna be something that's feasible for, I don't think, any of us (. . .) We're very limited 'cause we have a budget that we have to stick to for the entire year, and there is no leeway often time in those. (C02)

One HCP described her perception that while PBT on the split-belt treadmill used in the present study was not affordable, manual PBT may be more feasible to implement in her clinic.

> I think manually, I think we can implement something super-easy. The split treadmill would be. . . cost-wise, a problem. (C02)

Ethicality

Older Adults. Prospectively and retrospectively, many older adults perceived PBT as a good fit within their value system concerning overall health and fitness, citing a desire to maintain a level of functional independence as a motivating factor.

> I think it's going to help me a lot in keeping healthy, and I don't wanna sit in a chair and watch TV all day. (. . .) I think it'll be a big help to get me outta the house. [laughter] (P02)

Participants generally agreed that PBT fit within their values regarding fall prevention. Although several noted that they had not specifically thought about fall prevention before the interview, this was not perceived as a barrier to participation.

> I thought it was really good. I think it's a good idea for all of us to be aware of falling and being in a position of vulnerability, tripping or falling because on ice or on anything like that it can happen so fast that whether or not you have the opportunity to avoid it. . . it's a good idea. (P34)

Awareness of the potential consequences of falling and the importance of fall risk reduction was identified as a facilitator.

> [It's] sometimes the beginning of the end, whether if they break a hip, if they break an arm, if they break a leg, it's so hard for elderly people to recover from that, and you know they lose that ability to live independently, so it's pretty important, I think to prevent falls and to help yourself. (S34)

Several participants indicated they valued contributing to a scientific study, specifically noting an appreciation for the translational nature of the project.

HCPs. All HCPs prospectively and retrospectively agreed that PBT fit within their views on health and fall prevention and perceived it to be appropriate for the older adults in their community, both of which were identified as facilitators.

> I think it'll be very appropriate because there's a lot of people in our elderly population (. . .) I think it would be good for them. (C04)

Before delivering PBT, one HCP worried it may be too difficult for many older adults. After delivering the PBT program, however, she described how the individualization and scalability of perturbation intensity helped lessen her concern.

> Initially, I was concerned about their physical activity level, but I don't think that's something I'm as concerned about, considering you can titrate it to their various fitness levels and abilities. (C01)

Intervention Coherence

Older Adults. Prospectively, most older adults were able to communicate the purpose of PBT to the extent that it is intended to help them learn to fall or to catch themselves in a fall. When asked about the purpose of the training two older adults reported that that purpose was:

> To keep me from falling (P33); to teach me to catch myself when I fall (P31);

However, other older adults attributed the training to better balance, as evidenced by one older adult who claimed,

> . . .it's to make balance easier or better for me so that I don't fall (P26)

Retrospectively, older adults were able to state that the purpose was to improve balance and were able to expand on this idea. While a few perceived the purpose of the intervention to be related to increasing balance awareness or building balance confidence, others accurately identified that PBT aims to improve balance recovery specifically and provided more detailed explanations.

> To teach me to catch myself when I fall (. . .) So the idea is if you stumble in here then (when) you're in the real world you'll have muscle memory. (P31)

Further, those who demonstrated a more comprehensive understanding of the specific and reactive nature of PBT and its potential to translate to real-world losses of balance tended to perceive PBT as more effective and identified as a facilitator of participation.

HCPs. Prospectively, HCPs had previous knowledge regarding the use of PBT to improve balance recovery in older adults. One area of interest to the HCPs was the protocol that would be used in the study.

> I'm not sure yet about the protocol. If there is a standardized protocol. . .that'd be interesting to see what the dosage needs to be. . .(C01)

During the weekly PBT sessions, HCPs received training on PBT delivery which included education on the efficacy and mechanisms of PBT. As such, all HCPs fully recognized the purpose of PBT and this question was not addressed in retrospective interviews.

Opportunity Cost

Older Adults. Prospectively, the majority of older adults reported that participation would not impact their ability to participate in PBT. When asked if they would have to give up any current activities to participate in PBT, many older adults reported that they made time for the training. One older adult stated,

> I scheduled [the training] on purpose. (P15), and another My schedule's pretty flexible. (P25)

Retrospectively, no participants reported having to give up any activities to participate in the PBT program. There were no reported negative impacts from PBT on other recreational or occupational activities. Further, most reported that training at the community center, which was in the center of town, was a convenient location. Many had to commute from out of town for training but did not identify the location as either a facilitator or a barrier to participation.

> I really don't feel like I had to give up anything. . .they worked around a time schedule that worked for me (P34).

HCPs. Prospectively, HCPs reported that PBT would have a positive opportunity cost in that it would support other work occurring within their clinics. One HCP stated,

> I think that [PBT] would be easy to implement so long as the treadmill or equipment could be applied to not only geriatric population but maybe other types of conditions as well (C01)

Retrospectively, HCPs agreed that the opportunity costs associated with facilitating PBT were acceptable. The only potential opportunity cost identified was the time required for training, but it was not reported to be a barrier. Most identified the compatibility of PBT with their current balance training protocols as a facilitator for the low opportunity costs.

> It went right with what we're already doing. (C02)

> At this point, I foresee no negative impacts on like insurance reimbursement, anything like that with it, so I imagine it would be mostly positive as well. (C01)

Perceived Effectiveness

Older Adults. Older adults reported in pre-intervention interviews the perception that PBT would be effective. In post-intervention interviews, many older adults described positive psychological effects including gains in balance confidence and an increased awareness of their balance and perceived threats to balance. Regarding gains in physical abilities related to balance, a few participants noted perceived changes in gait. One described how increased balance awareness led her to change her normal walking gait in a manner that she perceived as more effective.

> I'm very glad I did it. I think it improved my walking. (. . .) I feel I pick up my toes better when walking so I shouldn't fall. (. . .) I consciously take bigger steps after the training, and I wasn't doing that before. (P11)

However, concerning physical abilities, most older adults perceived that their abilities either stayed the same or that the changes were imperceptible. Many participants cited the fact that they had not experienced a slip, trip or fall during the study as a reason potential physical changes were not perceptible. The perception of little physical change was not identified as a barrier to participation in the program.

> I can't honestly say that I did because I haven't tripped or done anything of that kind. (P14)

One participant noted that while she did not observe any physical gains, they expected some may have occurred because of PBT.

> (. . .) I mean I haven't fallen, so it's hard to tell. (. . .) But I think the training should help with catching myself. (P05)

Overall, older adults reported positive psychological changes associated with PBT, yet the effectiveness of PBT for physical changes was less perceptible by older adults.

HCPs. Prospective perceived effectiveness was high for all HCPs. Prior knowledge of PBT research and educational training provided by researchers before delivery were identified as facilitators.

> Oh no, I think they'd all be positive. I do think oftentimes, it's more than what they are experiencing at their baseline, so I'm expecting mostly positive effects. (C01)

Retrospectively, similar to older adults, HCPs reported difficulty observing physical improvements resulting from balance training due to the duration of the PBT protocol and the infrequent nature of slips, trips, and stumbles. However, the lack of observable physical improvements was not reported as a barrier. HCPs reported receiving positive feedback from older adults regarding the PBT program which was identified as a facilitator of perceived effectiveness.

> I have heard good feedback from community members that are doing it. (. . .) I had a lot of them be like, "Oh, I feel better. I feel like it's helping. I feel like I'm walking better, taking bigger steps". So, I definitely heard good feedback from the [participants]. I haven't heard any negative. (C02)

Self-Efficacy

Older Adults. According to prospective interviews, older adults felt that they would be able to successfully complete the PBT training. From retrospective interviews, all who completed the PBT program reported they felt able to successfully participate in PBT throughout the program. Most older adults described an increase in self-efficacy throughout the PBT program. Several expressed lower self-efficacy during earlier PBT sessions, especially after experiencing more difficult perturbations or near-/unsuccessful balance recovery attempts.

> The most nerve-wracking part was the waiting. The anticipation that it was gonna be more difficult than it was. (. . .) I think I got used to it in the next sessions. But the first one definitely when we're just getting used to it, I expected it to be worse than it was. (P33)

Many of these participants went on to describe how feelings of apprehension were replaced with feelings of accomplishment and growing confidence in their abilities as the PBT program progressed. One described her gains in confidence in detail:

> There was one time I got a little spooked (. . .) I did lose my balance a little but didn't fall. So I was really proud of myself. (. . .) It built my confidence (. . .) and it reassured me that if I trip, chances are I'm not going to fall, I'll catch myself. And I like that. (P14)

HCPs. Based on their prior knowledge of the benefits of PBT, all HCPs prospectively agreed they felt capable of efficiently implementing PBT on their own in their clinics. When one HCP was asked about their ability to implement PBT, the HCP responded,

> I think that it would be easy to implement (C01).

Retrospectively, HCPs maintained and reinforced their ability to implement PBT. One HCP described that she felt the efficient nature of PBT was a facilitator of her ability to implement it in the clinic.

> I think it was very efficient. The time that it actually took the participants to run through the protocol was really quick and actually quite streamlined. (. . .) [I feel] very capable. It seems really easy to implement, just like any other protocol that would be lined out, easy to adjust, easy to scale. (C01)

Thus, based on the HCP's time observing and assisting with the implementation of PBT, they stated that they felt capable in their ability to implement PBT in a clinical setting.

Discussion

The purpose of this study was to assess the prospective and retrospective acceptability of a community-based PBT program for older adult participants and HCPs. Understanding the acceptability of PBT for both older adults and HCPs helps to identify potential facilitators and barriers, which is a necessary step toward implementing PBT in rural communities. Our results indicate that both older adults and HCPs perceived the PBT program to be generally acceptable but also identified perceived barriers and considerations for future community-based PBT interventions. Since there was often overlap between the components of the TFA concerning the perceived acceptability of PBT, we structured the discussion in three sections: (1) Facilitators, which discusses themes identified as facilitators of participation in PBT for both older adults and HCPs, (2) Community Education, which discusses the influence educational seminars provided to the community may have had on the perceived acceptability of the PBT program, and (3) PBT equipment, which is discussed in its own section as a barrier to perceived acceptability.

Facilitators of Acceptability

Overall, the older adults in this study perceived PBT to be acceptable based on the prospective and retrospective interviews utilizing the TFA to attain the perceptions of acceptability. One component of the TFA is self-efficacy. Gains in self-efficacy and high perceived efficacy were described as facilitators of participation in PBT by older adults. These findings comport with previous reports that while older adults may be initially apprehensive due to the unpredictable nature of PBT (Miller et al., 2018; Okubo, Brodie, et al., 2019), these feelings of apprehension tend to be replaced by gains in self-efficacy as training progresses (Gerards et al., 2022). A novel finding from the present study was the theme of "fall awareness," which emerged during pre-PBT interviews and was developed to represent an awareness by older adults of the potential consequences of falling as a facilitator to the decision to participate in PBT. Fall awareness was mostly described by older adults who knew someone in their social circle who had experienced a fall and subsequently lost a degree of functional independence. For older adults in this study, prospective fall awareness appears to have facilitated high prospective perceptions of ethicality in PBT. For instance, most older adults in the present study described PBT as fitting within their views on health and fall prevention. In contrast, Gerards et al. found that older adults often had not thought of fall prevention before PBT or that they felt they did not need it (Gerards et al., 2022).

Community Education. Another facilitator of participation in the PBT program was the inclusion of community education seminars. Notably, one free optional educational seminar was offered to all members of the local community by the research team in partnership with local extension agents before any discussions regarding the research project. Seminars offered general information on falls and fall risk reduction strategies for older adults, education on different types of balance (i.e., static vs. dynamic and reactive vs. proactive) and covered balance training resources, including PBT. While it was not explicitly described by older adults, we suggest these seminars may have facilitated the theme of fall consequence awareness as well as the high levels of prospective perceived ethicality described by older adults in the present study. Indeed, Hawley-Hague et al. (2014) reported that promoting positive benefits is a crucial factor in older adults' perception of fall prevention technology. Others demonstrated that intent to participate in balance training is related to both support from health professionals (Lindgren De Groot et al., 2011) and the perception that family, friends, and HCPs would approve of their participation (Yardley et al., 2007).

Local HCPs also demonstrated high levels of perceived ethicality toward PBT prospectively and retrospectively. HCPs described PBT as effective and highly compatible with their existing fall prevention practices and did not perceive there would be a high burden or opportunity cost associated with delivering PBT. Previously, Mansfield, Danells, et al. (2021) reported that a lack of knowledge regarding PBT appeared to be a primary barrier to implementing PBT in the clinic among HCPs. However, lack of knowledge was not described as a barrier by HCPs in the present study. Again, we suggest this may be attributed to the brief educational training provided to HCPs by the research team before delivering PBT.

Considering the high prospective levels of perceived efficacy and ethicality described by older adults and HCPs, we suggest that future community-based PBT programs provide educational opportunities to enhance the prospective acceptability of PBT.

Barriers to Acceptability

PBT Equipment

Older Adults. Several aspects of the treadmill were described as off-putting by older adults in the present study including the lack of handrails and control console, the split belt design, and the elevation of the treadmill deck. While these features were not described as barriers to participation in PBT, it is notable that Gerards et al. (2022) reported older adults described the PBT equipment and training environment as a facilitator to participation. Because our treadmill was designed for use in the community it had to be portable and more affordable than laboratory-grade alternatives. As such, there were several notable differences between the treadmill used in this study and the treadmill used by Gerards et al. (2022). Firstly, due to the portable design, the treadmill deck was approximately 30cm above the floor whereas the treadmill in Gerards et al. (2022) was built into a platform such that the participant is at floor level when using the treadmill. Second, the treadmill in Gerards et al. (2022) did not have handrails or a control panel. Rather, they utilized virtual environments displayed on a 180° screen in front of participants throughout training and found that most older adults described them as positive and enhancing their experience with PBT. While the use of virtual environments was not plausible in the present study due to portability and financial constraints, their use may have created a more immersive experience and attenuated concerns regarding the lack of handrails and a control panel.

Healthcare Providers. Despite the portability of the treadmill used in the current study and the fact that it was an order of magnitude less expensive than laboratory-grade alternatives, all HCPs in the present study described the financial burden of acquiring a mechanical perturbation system, such as the treadmill, as a seemingly insurmountable barrier. Similarly, Mansfield, Danells, et al. (2021), surveyed HCPs regarding perceptions of PBT and found that purchasing PBT equipment was perceived as a barrier by over half of the HCPs surveyed. Although the present study asked HCPs about their perceptions regarding PBT using a perturbation treadmill, there are many forms of PBT which can include alternative low-tech methods of perturbation delivery that do not require mechanical perturbation systems. One such low-tech method is manual PBT, which involves therapist-applied perturbations. The goal of manual PBT is the same as any other PBT intervention; however, perturbations are delivered by an individual rather than a mechanical system. For a more detailed description of manual PBT, we refer readers to Mansfield, Inness, et al. (2021). An HCP in the present study indicated she perceived manual PBT as a much more feasible form of PBT in the clinic and suggested that without the need for a mechanical perturbation system, the financial and logistical burden of delivering PBT would be much lower.

Considering perceived barriers relating to mechanical perturbation equipment found in the present study and reported previously by Mansfield, Danells, et al. (2021), it appears that low-tech alternatives such as manual PBT may be a more acceptable and feasible means of delivering PBT in the community. However, there have been few randomized controlled trials to investigate the efficacy of PBT outside the lab and even fewer still that have compared different methods of PBT (Gerards et al., 2017; McCrum et al., 2022). As such, there is a clear need for future research to evaluate the effects of different PBT methods, including manual PBT, on falls in daily life for community-dwelling older adults as well as the feasibility and acceptability of conducting different PBT methods in a community setting.

To our knowledge, this is the first study to evaluate the acceptability of PBT from multiple temporal perspectives and evaluate the perceptions of both older adults and healthcare professionals simultaneously. Additionally, the community setting of the present study provides insights into perceived barriers and facilitators in a different light than previous investigations conducted in laboratory settings. There are several limitations to be considered when interpreting the results of this study. Although a researcher (DT) who was not involved in the PBT intervention conducted most of the interviews, JW conducted pre-training interviews for six participants. No new themes emerged from these interviews but JW's involvement in the PBT intervention may have influenced participant responses. The study was co-designed through the CES and local agents assisted with recruitment, therefore perceptions of PBT described by older adults may differ from a PBT intervention delivered exclusively in a clinical environment. Our sample size ($n = 19$) must be considered when interpreting the results of this study. Due to the extremely low population density of the communities where this research took place as well as seasonal limitations (i.e., roads that are inaccessible during winter and harvest in the summer), there was only a window of a few months where participant recruitment and data collection were possible. Additionally, our sample of 19 older adults was comprised solely of white, American, older adults and was predominantly female; as such, their perspectives may not accurately reflect those of all older adults. Similarly, our sample of three HCPs and their previous knowledge of PBT, which was comprised exclusively of white American females, is not large enough to draw any definitive conclusion and does not reflect the perspectives of all HCPs toward PBT. Lastly, the self-selection of participants in the study may preclude those older adults who have a fear of falling and thus may have a different perception of the acceptability of PBT. Future research should investigate perceptions of PBT in more diverse settings and groups of older adults.

Conclusion

Our findings suggest that a community-based PBT program is acceptable to community-dwelling older adults. Gains in self-efficacy, balance confidence, and high perceived efficacy were identified as facilitators of participation. Healthcare professionals identified low levels of burden and opportunity cost as well as high perceived effectiveness and ethicality as facilitators of PBT delivery. Pre-PBT educational seminars may have increased prospective acceptability for both older adults and healthcare professionals. However, some older adults reported anxiety regarding the design of the perturbation treadmill and all HCPs described the financial burden of acquiring a mechanical perturbation system as a substantial barrier to delivering PBT. Taken together, these results suggest PBT is acceptable in the community, but also demonstrate a need for training methods that are more feasibly implemented outside of the laboratory. Further investigation of methods of PBT delivery is warranted to further understand the acceptability of PBT to older adults and HCPs in the community. Specifically, investigations into low-tech alternatives such as manual PBT may offer solutions.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the National Center for Advancing Translational Sciences of the National Institutes of Health under Award Number TL1 TR002318 (JW). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Ethical Approval

This study involves human participants and was approved by the Montana State University Institutional Review Board, MSU IRB# 2022-204. Participants gave written informed consent before taking part in the study.

ORCID iDs

Justin Whitten https://orcid.org/0000-0002-2237-0462
David Graham https://orcid.org/0000-0001-7338-3995

Supplemental Material

Supplemental material for this article is available online.

References

Bergen, G., Stevens, M. R., & Burns, E. R. (2016). Falls and fall injuries among adults aged ≥65 years—United States, 2014. *MMWR. Morbidity and Mortality Weekly Report*, *65*(37), 993–998. https://doi.org/10.15585/mmwr.mm6537a2

Blake, A. J., Morgan, K., Bendall, M. J., Dallosso, H., Ebrahim, S. B. J., Arie, T. H. D., Fentem, P. H., & Bassey, E. J. (1988). Falls by elderly people at home: Prevalence and associated factors. *Age and Ageing*, *17*(6), 365–372. https://doi.org/10.1093/AGEING/17.6.365

Borrelli, B., Sepinwall, D., Bellg, A. J., Breger, R., DeFrancesco, C., Sharp, D. L., Ernst, D., Czajkowski, S., Levesque, C., Ogedegbe, G., Resnick, B., & Orwig, D. (2005). A new tool to assess treatment fidelity and evaluation of treatment fidelity across 10 years of health behavior research. *Journal of Consulting and Clinical Psychology*, *73*(5), 852–860. https://doi.org/10.1037/0022-006X.73.5.852

Brooks, J., McCluskey, S., Turley, E., & King, N. (2015). The utility of template analysis in qualitative psychology research. *Qualitative Research in Psychology*, *12*(2), 202–222. https://doi.org/10.1080/14780887.2014.955224

Burns, E., Kakara, R., & Moreland, B. (2023). *A CDC compendium of effective fall interventions: What works for community-dwelling older adults* (4th ed.). Centers for Disease Control and Prevention, National Center for Injury Prevention and Control,

Devasahayam, A. J., Farwell, K., Lim, B., Morton, A., Fleming, N., Jagroop, D., Aryan, R., Saumur, T. M., & Mansfield, A. (2022). The effect of reactive balance training on falls in daily life: An updated systematic review and meta-analysis. *Physical Therapy*, *103*(1), pzac154. https://doi.org/10.1093/PTJ/PZAC154

Extension | National Institute of Food and Agriculture. (2022). Retrieved April 8, 2023, from https://www.nifa.usda.gov/about-nifa/how-we-work/extension

Gerards, M. H. G., Marcellis, R. G. J., Poeze, M., Lenssen, A. F., Meijer, K., & de Bie, R. A. (2021). Perturbation-based balance training to improve balance control and reduce falls in older adults—Study protocol for a randomized controlled trial. *BMC Geriatrics*, *21*(1), 1–12. https://doi.org/10.1186/s12877-020-01944-7

Gerards, M. H. G., Marcellis, R., Senden, R., Poeze, M., de Bie, R., Meijer, K., & Lenssen, A. (2023). The effect of perturbation-based balance training on balance control and fear of falling in older adults: a single-blind randomised controlled trial. *BMC Geriatrics*, *23*(1), 305. https://doi.org/10.1186/s12877-023-03988-x

Gerards, M. H. G., 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. https://doi.org/10.1111/GGI.13082

Gerards, M. H. G., Sieben, J., Marcellis, R., de Bie, R. A., Meijer, K., & Lenssen, A. F. (2022). Acceptability of a perturbation-based balance training programme for falls prevention in older adults: A qualitative study. *BMJ Open*, *12*, 56623. https://doi.org/10.1136/bmjopen-2021-056623

Grabiner, M. D., Donovan, S., Bareither, M., Lou, 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. https://doi.org/10.1016/j.jelekin.2007.06.009

Hawley-Hague, H., Boulton, E., Hall, A., Pfeiffer, K., & Todd, C. (2014). Older adults' perceptions of technologies aimed at falls prevention, detection or monitoring: A systematic review. *International Journal of Medical Informatics*, *83*(6), 416–426. https://doi.org/10.1016/J.IJMEDINF.2014.03.002

Hommel, K. A., Hente, E., Herzer, M., Ingerski, L. M., & Denson, L. A. (2013). Telehealth behavioral treatment for medication nonadherence: A pilot and feasibility study. *European Journal of Gastroenterology & Hepatology*, *25*(4), 469. https://doi.org/10.1097/MEG.0B013E32835C2A1B

Huxham, F. E., Goldie, P. A., & Patla, A. E. (2001). Theoretical considerations in balance assessment. *Australian Journal of Physiotherapy*, *47*(2), 89–100. https://doi.org/10.1016/s0004-9514(14)60300-7

Lindgren De Groot, G. C., Fagerström, L., Cathrine, G., & De Groot, L. (2011). Older adults' motivating factors and barriers to exercise to prevent falls. *Scandinavian Journal of Occupational Therapy*, *18*(2), 153–160. https://doi.org/10.3109/11038128.2010.487113

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://doi.org/10.1007/S001980070086

Mansfield, A., Danells, C. J., Inness, E. L., Musselman, K., & Salbach, N. M. (2021). A survey of Canadian healthcare professionals' practices regarding reactive balance training. *Physiotherapy Theory and Practice*, *37*(7), 787–800. https://doi.org/10.1080/09593985.2019.1650856

Mansfield, A., Inness, E. L., Danells, C. J., Jagroop, D., Musselman, K. E., Salbach, N. M., & Kochanowski, J. (2021). Implementing reactive balance training in rehabilitation practice: A guide for healthcare professionals. https://kite-uhn-contents.s3.ca-central-1.amazonaws.com/ReBal-docs/Training-manual_10September+2021.pdf

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. https://doi.org/10.2522/PTJ.20090070

Margalit, N., Kurz, I., Wacht, O., Mansfield, A., & Melzer, I. (2023). A survey of Israeli physical therapists regarding reactive balance training. *BMC Geriatrics*, *23*(1), 656. https://doi.org/10.1186/s12877-023-04356-5

McCrum, C., Bhatt, T. S., Gerards, M. H. G., Karamanidis, K., Rogers, M. W., Lord, S. R., & Okubo, Y. (2022). Perturbation-based balance training: Principles, mechanisms and implementation in clinical practice. *Frontiers in Sports and Active Living*, *4*, 1015394. https://doi.org/10.3389/fspor.2022.1015394

Miller, C. T., Teychenne, M., & Maple, J. L. (2018). The perceived feasibility and acceptability of a conceptually challenging exercise training program in older adults. *Clinical Interventions in Aging*, *13*, 451–461. https://doi.org/10.2147/CIA.S154664

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., Sturnieks, D. L., Brodie, M. A., Duran, L., & Lord, S. R. (2019). Effect of reactive balance training involving repeated slips and trips on balance recovery among older adults: A blinded randomized controlled trial. *The Journals of Gerontology: Series A*, *74*(9), 1489–1496. https://doi.org/10.1093/gerona/glz021

Pai, Y.-C., Bhatt, T., Wang, E., Espy, D., & Pavol, M. J. (2010). Inoculation against falls: Rapid adaptation by young and older adults to slips during daily activities. *Archives of Physical Medicine and Rehabilitation*, *91*(3), 452–459. https://doi.org/10.1016/j.apmr.2009.10.032

Sekhon, M., Cartwright, M., & Francis, J. J. (2017). Acceptability of healthcare interventions: An overview of reviews and development of a theoretical framework. *BMC Health Services Research*, *17*(1), 1–13. https://doi.org/10.1186/s12913-017-2031-8

Sherrington, C., Fairhall, N., Kwok, W., Wallbank, G., Tiedemann, A., Michaleff, Z. A., Ng, C. A. C. M., & Bauman, A. (2020). Evidence on physical activity and falls prevention for people aged 65+ years: Systematic review to inform the WHO guidelines on physical activity and sedentary behaviour. *International Journal of Behavioral Nutrition and Physical Activity*, *17*(1), 1–9. https://doi.org/10.1186/S12966-020-01041-3/FIGURES/3

Talbot, L. A., Musiol, R. J., Witham, E. K., & Metter, E. J. (2005). Falls in young, middle-aged and older community dwelling adults: Perceived cause, environmental factors and injury. *BMC Public Health*, *5*, 1–9. https://doi.org/10.1186/1471-2458-5-86

Tombaugh, T. N., & McIntyre, N. J. (1992). The mini-mental state examination: A comprehensive review. *Journal of the American Geriatrics Society*, *40*(9), 922–935. https://doi.org/10.1111/J.1532-5415.1992.TB01992.X

Wang, Y., Wang, S., Lee, A., Pai, Y. C., & Bhatt, T. (2019). Treadmill-gait slip training in community-dwelling older adults: Mechanisms of immediate adaptation for a progressive ascending-mixed-intensity protocol. *Experimental Brain Research*, *237*, 2305–2317.

Yardley, L., Donovan-Hall, M., Francis, K., & Todd, C. (2007). Attitudes and beliefs that predict older people's intention to undertake strength and balance training. *The Journals of Gerontology: Series B*, *62*(2), P119–P125. https://doi.org/10.1093/GERONB/62.2.P119

CHAPTER FIVE

CONCLUSION

Falls represent a major health concern for older adults, leading to a substantial financial and logistical burden on the healthcare system[1,3–8]. Prominent organizations such as the U.S. Department of Health and Human Services (HHS) and the American College of Sports Medicine (ACSM) recognize falls as a key challenge facing aging populations and recommend increasing physical activity and general exercise as a primary strategy for fall prevention. However, despite these recommendations, fall and fall-related death rates among older adults in the U.S. have continued to rise over the past decade[10]. The increasing incidence of falls suggests that current fall prevention paradigms are insufficient, highlighting the need for a more targeted and effective approach.

One potential explanation for the limited success[29,52] of general physical activity in reducing fall risk is that it does not directly train the balance recovery mechanisms most relevant to preventing falls. Falls often occur due to sudden, unexpected disruptions in stability, such as slips, trips, or stumbles, which require rapid and effective reactive balance responses. However, most conventional assessments of fall risk focus on functional measures that capture voluntary or proactive movements rather than reactive balance control. As a result, the current tools used to predict fall risk and design interventions may not adequately address the underlying mechanisms of fall recovery.

More specifically, functional capacity and muscle quality appear to be key components that contribute to an individual's ability to respond to balance challenges. Evidence suggests that muscle quality, rather than just strength or cross-sectional area, plays an important role in balance recovery, particularly in muscles responsible for rapid postural adjustments. The hamstrings, for example, appear to be heavily involved in stabilizing the body during recovery from a forward loss of balance. Emerging research indicates that lower limb muscle quality, particularly in the biceps femoris, may be an important factor influencing an individual's ability to recover balance effectively. Given that muscle function plays a critical role in balance recovery, identifying accessible methods to assess muscle quality could improve fall risk screening and intervention strategies. Until recently, assessment of muscle quality was limited to isokinetic dynamometry or complex forms of medical imaging such as MRI, but recent advances in standard B-mode ultrasound may provide a more accessible screening tool for identifying individuals at greater fall risk.

Since general physical activity and conventional balance training have not effectively reduced fall risk in community-dwelling older adults, interventions targeting reactive balance control are needed. Perturbation-Based Balance Training (PBT), which exposes individuals to controlled balance disruptions to improve recovery responses, has emerged as a promising approach. Unlike conventional balance training, which primarily targets proactive balance control through voluntary movements, PBT specifically trains the rapid, involuntary responses required to recover from unexpected loss of stability. However, despite growing evidence supporting its effectiveness, PBT has not yet been widely adopted in community or clinical settings. For PBT to be implemented on a broad scale, it is critical to assess whether older adults and healthcare providers view it as acceptable and feasible.

These gaps informed the overarching aims of this dissertation: to examine key contributors to reactive balance control and fall risk in older adults, as well as to assess the feasibility of targeted interventions aimed at improving balance recovery and reducing fall risk. To address these aims, three studies were conducted. Study 1 examined the relationship between habitual physical activity and prospective fall incidence in community-dwelling older adults. The findings indicated that general activity levels and functional assessments did not predict future falls, suggesting that traditional assessment tools may fail to capture critical components of fall risk, particularly reactive balance control. Study 2 investigated the role of lower limb muscle quality in balance recovery. Results demonstrated that biceps femoris muscle quality was a significant predictor of Maximum Recoverable Lean Magnitude (MRLM) and Choice Stepping Reaction Time (CSRT-M), suggesting that hamstring muscle quality plays a key role in balance recovery. Study 3 evaluated the acceptability and feasibility of a community-based perturbation-based balance training (PBT) program among older adults and practitioners. Participants generally viewed PBT as an acceptable and practical intervention, reinforcing the potential for real-world implementation.

Together, these studies highlight the need for a paradigm shift in fall prevention—away from traditional assessments and interventions that focus on general activity or proactive balance training and toward a more targeted approach that accounts for muscle quality, reactive balance control, and the feasibility of emerging interventions like PBT. The following sections will integrate these findings, discuss their theoretical and practical implications, and outline future research directions.

Summary of Key Findings

Physical Activity and Future Falls

Chapter One examined the relationship between habitual physical activity and prospective fall incidence in a cohort of 104 community-dwelling older adults. The findings indicated no significant association between baseline measures of physical activity, physical function, or lower limb strength and future fall incidence. This result aligns with previous research suggesting that low-intensity habitual activities, such as leisure activities [53] or walking[29], as well as low amounts of moderate physical activity [25], are insufficient on their own to meaningfully reduce fall risk. While some exercise-based interventions, particularly those incorporating multi-component exercise programs, have demonstrated efficacy in fall prevention[29], the steady increase in fall rates among older adults suggests that the effectiveness of these conventional approaches may be limited compared to higher-intensity, task-specific interventions such as perturbation-based balance training.

Notably, clinical assessments of physical function, including the Timed-Up and Go[54], Short-Form 36 Questionnaire[55], or the Modified Baecke Physical Activity Questionnaire[56], did not differ between older adults who fell and those who did not. This finding suggests that traditional assessments of physical activity and function may not capture the key mechanisms underlying fall risk, particularly reactive balance control. Given that the majority of falls occur due to unexpected perturbations, conventional assessments and interventions may overlook critical elements of balance recovery. These results highlight the need for more targeted assessment tools and intervention strategies that specifically address reactive balance responses rather than relying solely on general measures of physical activity or physical function.

Muscle Quality and Reactive Balance Control

Given the need for more precise assessments of balance control, Chapter Two examined the relationship between lower limb muscle quality and reactive balance control. Standard B-mode ultrasound images of the biceps femoris, vastus lateralis, and medial gastrocnemius were collected from eighteen participants (12 older adults, 6 younger adults). Reactive balance control was assessed using Maximum Recoverable Lean Magnitude (MRLM)[12] and Modified Choice Stepping Reaction Time (CSRT-M)[57]. After identifying and removing a single influential data point, biceps femoris muscle quality emerged as a significant predictor of MRLM in older adults, reinforcing the growing evidence that muscle composition plays a key role in fall prevention.

These findings align with previous research demonstrating that age-related declines in lower limb muscle quality contribute to impaired balance control in older adults[58–60]. Additionally, prior studies have highlighted the importance of muscular power[61], and specifically the role of the biceps femoris[62], in balance recovery, particularly in response to forward loss of balance.

These results support the theory that reactive balance control is a distinct quality that requires specialized assessment and training to improve. Furthermore, it suggests that biceps femoris muscle quality may serve as a valuable marker of fall risk in older adults. The findings also highlight the potential of B-mode ultrasound as a targeted fall risk screening tool, offering a more precise alternative to conventional balance assessments such as the Timed Up and Go or general physical activity measures.

The Acceptability of PBT

Having established that specific methods are required to assess and improve balance control in older adults, Chapter Three evaluated the acceptability of Perturbation-Based Balance Training (PBT) among both community-dwelling older adults (n = 19) who participated in the training and local healthcare practitioners (n = 3) involved in delivering the program. Semi-structured interviews based on the Theoretical Framework of Acceptability[51] were conducted with both groups before and after participation to assess their perceptions of PBT as a fall prevention intervention.

Overall, the PBT program was found to be acceptable to both older adults and healthcare practitioners. One key factor influencing acceptability was the type of equipment used to deliver the training. Prior studies have implemented high-tech perturbation treadmills that incorporate virtual reality [49], which has been reported as a facilitator of acceptability. However, in this study, a lower-cost, portable treadmill was used to improve accessibility. While the low-tech nature of the treadmill was not directly cited as a barrier to participation, some practical limitations related to portability, such as the treadmill deck height and lack of a display, were noted by participants. Importantly, the unpredictable nature of the perturbations—a potential concern for acceptability—was not perceived as a significant barrier by older adults.

From an implementation perspective, healthcare providers identified cost as a major barrier to real-world adoption of PBT. While the treadmill used in this study was less expensive than other perturbation devices, its price still posed a challenge for widespread community-based implementation. Several healthcare providers inquired about alternative, lower-cost methods of delivering PBT, such as manually induced perturbations[63]. Although manual PBT has the potential to be more financially feasible, its effectiveness compared to mechanical PBT remains unclear[34]. This distinction presents an important avenue for future research, as determining whether manual perturbations provide the same benefits as treadmill-based PBT will be critical for scaling the intervention to broader community and clinical settings.

Specificity is King: Why General Methods Aren't More Effective

Despite widespread recommendations for general physical activity and conventional balance training as fall prevention strategies[26,29,64], the continued rise in fall incidence suggests that these interventions may not address the most critical components of fall risk[35]. While general physical activity and exercise-based interventions offer numerous health benefits, their effectiveness in reducing fall rates is limited[25,28,29,52]. A key reason for this limitation is that they fail to adequately train the neuromuscular mechanisms required for effective balance recovery[65]. To fully understand why this is the case, it is necessary to examine the underlying components of balance control and the specific demands associated with fall recovery.

Understanding Balance Control

Balance is not a singular quality but a foundational system that supports various daily activities. Tasks such as sitting on a sofa, carrying a child, hanging a picture, or navigating a crowded street require distinct control of muscle tone and postural control. Importantly, balance cannot be separated from the task being performed or the environment in which it occurs[66]. As such, balance serves as the foundation for voluntary motor skills[67].

Under normal circumstances, balance is maintained by controlling both gravitational forces (to sustain posture) and acceleration forces (to maintain equilibrium)[67]. Acceleration forces may arise internally (as a result of self-initiated movement) or externally (due to an unexpected perturbation such as a slip, trip, or push). The ability to control these forces is what determines stability across different movement scenarios.

The demands placed on the balance control system depend on task complexity and environmental constraints. For example, standing quietly in a controlled setting requires little active engagement from the balance control system, whereas walking on an icy sidewalk or recovering from a sudden trip places far greater demands on equilibrium maintenance and reactive control mechanisms.

Key Subsystems of Balance Control

Several subsystems contribute to balance control, with static, dynamic, proactive, and reactive balance being particularly relevant[31,68]. Static Balance Control refers to maintaining a stable posture when no external forces challenge equilibrium, such as quietly standing or sitting. Dynamic Balance Control involves maintaining stability while moving, such as walking or running, and is closely linked to proactive balance control. Proactive (Anticipatory) Balance Control allows individuals to predict and prepare for expected perturbations. For example, transitioning from sitting to standing, adjusting posture while walking up an incline, or preparing for an impact while carrying a heavy object all require anticipatory adjustments. These mechanisms help maintain stability before a disturbance occurs. Reactive Balance Control governs the ability to restore stability after an unexpected perturbation has occurred[31,68]. It is engaged when postural equilibrium is disrupted beyond what proactive mechanisms can manage, such as when encountering a sudden slip or trip. Reactive mechanisms determine how effectively an individual can recover from balance loss.

Importantly, reactive balance control differs from proactive balance control because it requires rapid, reflexive responses to unanticipated challenges. In contrast, proactive balance adjustments are planned and voluntary. If proactive balance control fails to prevent instability, reactive control must compensate to prevent a fall[68].

<u>Where Conventional Balance Training Falls Short</u>

Current recommendations from the American College of Sports Medicine (ACSM) outline several key principles for balance training in this population[26]. These include: (1) progressively reducing the base of support through increasingly challenging postures, such as transitioning from a two-legged stance to a semi-tandem, tandem, and ultimately single-leg stance; (2) incorporating dynamic movements that shift the center of gravity, such as tandem walking or executing controlled turns; (3) targeting postural muscle groups with exercises like heel and toe stands; and (4) reducing sensory input, for example, by practicing balance tasks with eyes closed. Similarly, the U.S. Department of Health and Human Services (HHS) recommends balance-focused activities such as walking in different directions (e.g., backward or sideways), yoga, tai chi, and water-based exercise programs as effective methods for improving stability and reducing fall risk[64].

A common theme among these conventional recommendations is that they are almost entirely static or quasistatic exercises that train proactive balance control, which governs anticipation of a predicted postural disturbance (i.e., changing from double to single limb support while standing)[69]. Conversely, the ability to recover from unexpected losses of balance is governed by reactive balance control (i.e., compensation for an unanticipated postural disturbance)[69]. Notably, the majority of falls in older adults occur as a result of an unexpected loss of balance such as an overground slip, trip, or stumble[32,33] and are therefore governed by reactive balance control[69]. Furthermore, balance performance is task specific[70], meaning improvements in proactive balance control do not also improve reactive balance ability[65]. Rather specific balance recovery training is needed to improve reactive balance control[71].

Perturbation-Based Balance Training

Perturbation-based Balance Training (PBT) is a newer method of fall prevention[72]. PBT utilizes repeated, unexpected, external perturbations (disruptions to balance) to trigger rapid reactions to recover postural stability[72,73]. Unlike conventional programs, the goal of PBT is to improve reactive balance control by training the ability to recover balance in destabilizing situations that mimic real-world losses of balance[34,72]. There are two key criteria for PBT programs: (1) training should involve external perturbations that induce a sudden motor response (i.e., perturbations should be unpredictable) and (2) perturbations should be intense enough to induce a loss of balance that would lead to a fall without execution of a sufficient motor response such as a step (i.e., the perturbations must be relatively large in magnitude)[34,72]. Perturbations may be applied during a variety of tasks ranging from standing or walking to activities of daily living. PBT is always conducted with the use of a safety harness and fall catch system, so participants can practice balance recovery in a manner that is simultaneously highly specific to the real world but safe and controlled, without the potential consequences of falling in the real world[72]. In terms of improvements in reactive balance control and fall risk reduction, PBT has been highly effective thus far[34,41,47,48,72,74–76].

A recent systematic review and meta-analysis found that older adults who participate in PBT programs experience a 40% reduction in fall rate when compared to those who participated in conventional balance training programs[73]. Notably, PBT is very potent and requires a lower training dose than conventional programs. For instance, Pai and Bhatt reported a 50% reduction in prospective fall incidence after a single session of PBT[41]. Meanwhile, Lurie et al. demonstrated that, for older adults who were referred to physical therapy for high fall risk, PBT resulted in a 57% lower risk of injurious falls than conventional balance training programs[75].

Implications and Future Directions

The existing literature on the efficacy of PBT aligns with the findings of this dissertation, further illustrating that fall risk in older adults is not a singular issue but rather a multidimensional problem requiring targeted assessment and intervention. The results of Chapter One demonstrated that habitual physical activity and conventional measures of physical function do not adequately predict falls, highlighting the need for more specific assessments of balance control. Chapter Two indicated that muscle quality, particularly in the biceps femoris, plays a key role in balance recovery, suggesting that neuromuscular factors may contribute to fall risk beyond what traditional assessments capture. Taken together, these findings reinforce the need for interventions like PBT, which specifically train the neuromuscular responses required for reactive balance recovery rather than relying on general physical activity or proactive balance training alone.

There remain several barriers to widespread adoption of PBT, including concerns regarding the acceptability of its unpredictable and intense nature among older adults, as well as the feasibility of implementing PBT outside of research settings. Chapter Three addressed these concerns and demonstrated that both older adults and healthcare practitioners found PBT acceptable, a finding that has been supported by additional research since its initial publication[77]. However, the financial feasibility of acquiring the equipment necessary to administer mechanical perturbations was identified as a substantial barrier by healthcare practitioners.

Therapist-applied or “manual” perturbations have emerged as a logical alternative that can be more easily implemented in clinical and community settings[72,78]. Compared to other PBT methods, manual perturbation training requires minimal equipment, primarily a safety harness and basic exercise tools that are already widely available in most community fitness and rehabilitation centers[78]. This makes manual PBT a highly attractive option for broader implementation. Although manual PBT has been successfully integrated into clinical settings for populations such as older adults with chronic stroke[79,80], Parkinson’s disease[81,82], and spinal cord injury [83], its application for otherwise healthy, community-dwelling older adults remains largely unstudied[73]. This is particularly notable given that key training variables such as perturbation magnitude, timing, and dosage are critical to the success of PBT[72]. Unlike mechanical perturbations, which can precisely control these variables, manual perturbations may be less predictable and more difficult to standardize[72]. While this does not necessarily negate manual PBT’s potential effectiveness, it does raise important questions regarding its ability to elicit comparable adaptations in reactive balance control.

Despite these challenges, manual PBT remains one of the most practical and scalable solutions for community-based fall prevention. Given its potential accessibility and cost-effectiveness, future research should prioritize determining whether manual perturbations can achieve comparable outcomes to mechanical PBT methods. Investigating the relative efficacy of low-tech PBT approaches is not only warranted—it is essential for integrating PBT into real-world fall prevention efforts. As falls continue to rise despite conventional interventions, ensuring that reactive balance training is both effective and widely accessible should be a key focus of future research.

Strengths and Limitations

Strengths

This dissertation provides new insights into fall risk, balance control, and exercise interventions by addressing critical gaps in assessment and intervention strategies. Study 1 reinforces that habitual physical activity and conventional assessments do not reliably predict fall risk. While prior research has suggested that structured exercise programs may reduce fall incidence, the findings of Study 1 reinforce that general activity levels alone are not sufficient, emphasizing the need for more specific assessments that capture reactive balance control rather than static or proactive balance measures. This provides further support for shifting fall risk screening away from broad functional tests and toward assessments that better reflect real-world balance challenges.

Study 2 explored the role of lower limb muscle quality in balance recovery, providing preliminary evidence that biceps femoris muscle quality may be associated with reactive balance control. While the study had a small sample size, it adds to the growing recognition that muscle quality, rather than just strength or mass, could be an important factor in balance recovery strategies. Additionally, this study suggests that B-mode ultrasound could serve as a practical tool for assessing muscle composition in the context of fall risk; however, further research is needed to determine its reliability and applicability in clinical or community-based settings.

Study 3 makes an important practical contribution by assessing the acceptability and feasibility of PBT among older adults and healthcare providers. While PBT has been well-documented as an effective method for improving reactive balance control, limited research has directly examined its real-world implementation potential. This study provides valuable insights into perceived barriers and facilitators, reinforcing that PBT is acceptable to both practitioners and participants but that cost and accessibility remain challenges. These findings lay the groundwork for future studies aimed at developing lower-cost or more scalable PBT delivery methods that can be implemented in community settings.

Finally, this dissertation integrates both quantitative and qualitative methodologies, allowing for a comprehensive evaluation of fall risk assessment, neuromuscular factors in balance recovery, and practical considerations for intervention adoption. The combination of objective balance measures (MRLM, CSRT-M) with participant and practitioner perspectives provides a well-rounded approach to understanding not only what interventions are effective but also how they might be feasibly implemented in clinical or community settings.

Limitations

Despite its contributions, this dissertation has several limitations that should be acknowledged. A key limitation is the small sample size in Study 2 ($n = 18$), limiting generalizability. While the findings provide valuable insights, larger studies are needed to confirm the relationship between muscle quality and balance recovery ability and improve the generalizability of the results. Additionally, the cross-sectional nature of the studies limits causal inferences. A longitudinal approach would allow for better assessment of how changes in muscle quality and balance control impact fall risk over time.

While promising, B-mode ultrasound has inherent limitations in assessing muscle quality. It provides structural information but does not capture real-time neuromuscular activation patterns during balance recovery, which may be an important factor in reactive balance control. Similarly, MRLM and CSRT-M, though widely used, do not fully replicate real-world fall scenarios, as most falls occur under dynamic, multidirectional conditions that are difficult to simulate in a controlled laboratory setting.

While Study 3 demonstrated acceptability and feasibility for PBT, it relied on a self-selected sample of participants, which may introduce bias. Additionally, barriers to implementation, including the cost of perturbation treadmills and accessibility in community settings, remain unresolved. Manual PBT is a feasible alternative, but its effectiveness compared to mechanical PBT remains unclear. Future research should compare manual and mechanical PBT interventions to determine whether low-tech, cost-effective solutions can provide similar benefits in improving reactive balance control and reducing fall risk.

Conclusion

Falls are a leading cause of injury and mortality among older adults, yet current fall prevention strategies have not effectively reduced fall rates. This dissertation's findings reinforce that conventional assessments and interventions, which primarily focus on general physical activity and proactive balance control, fail to address the critical neuromuscular mechanisms required for fall recovery.

Study 1 established that habitual physical activity and traditional functional assessments do not reliably predict future falls, highlighting the need for more specific balance screening tools. Study 2 provided preliminary evidence that lower limb muscle quality, particularly in the biceps femoris, may be a key factor in reactive balance control. Study 3 demonstrated that while perturbation-based balance training is a promising intervention for improving reactive balance, practical barriers such as cost and accessibility must be addressed for widespread adoption.

These findings highlight the need for specificity in fall prevention. Future research should refine assessment tools, develop cost-effective PBT interventions, and explore manual perturbation training for broader implementation. Closing these gaps is crucial for reducing fall risk in older adults.

CUMULATIVE REFERENCES CITED

Aguilar-Farías, N., Brown, W.J., & Peeters, G.G. (2014). ActiGraph GT3X+ cut-points for identifying sedentary behaviour in older adults in free-living environments. Journal of Science and Medicine in Sport, 17(3), 293–299.

Amireault, S., Baier, J.M., & Spencer, J.R. (2019). Physical activity preferences among older adults: A systematic review. Journal of Aging and Physical Activity, 27(1), 128–139. https://doi.org/10.1123/JAPA.2017-0234

Arampatzis, A., Karamanidis, K., & Mademli, L. (2008). Deficits in the way to achieve balance related to mechanisms of dynamic stability control in the elderly. *Journal of Biomechanics*, *41*(8), 1754–1761. https://doi.org/10.1016/j.jbiomech.2008.02.022

Australian Institute of Health and Welfare. (2022). Injury in Australia: Falls. https://www.aihw.gov.au/reports/injury/falls#More%20info

Baecke, J. A. H., Burema, J., & Frijters, J. E. R. (1982). A short questionnaire for the measurement of habitual physical activity in epidemiological studies. *The American Journal of Clinical Nutrition*, *36*(5), 936–942. https://doi.org/10.1093/AJCN/36.5.936

Barrett, R. S., Cronin, N. J., Lichtwark, G. A., Mills, P. M., & Carty, C. P. (2012a). Adaptive recovery responses to repeated forward loss of balance in older adults. *Journal of Biomechanics*, *45*(1), 183–187. https://doi.org/10.1016/j.jbiomech.2011.10.005

Barrett, R. S., Cronin, N. J., Lichtwark, G. A., Mills, P. M., & Carty, C. P. (2012b). Adaptive recovery responses to repeated forward loss of balance in older adults. *Journal of Biomechanics*, *45*(1), 183–187. https://doi.org/10.1016/j.jbiomech.2011.10.005

Berg, K. (2009). Balance and its measure in the elderly: a review. *Https://Doi.Org/10.3138/Ptc.41.5.240*, *41*(5), 240–246. https://doi.org/10.3138/PTC.41.5.240

Bergen, G., Stevens, M. R., & Burns, E. R. (2016). Falls and Fall Injuries Among Adults Aged ≥65 Years — United States, 2014. *MMWR. Morbidity and Mortality Weekly Report*, *65*(37), 993–998. https://doi.org/10.15585/mmwr.mm6537a2

Bhatt, T., Yang, F., & Pai, Y.-C. (2012). Learning to resist gait-slip falls: long-term retention in community-dwelling older adults. *Archives of Physical Medicine and Rehabilitation*, *93*(4), 557–564. https://doi.org/10.1016/j.apmr.2011.10.027

Blake, A. J., Morgan, K., Bendall, M. J., Dallosso, H., Ebrahim, S. B. J., Arie, T. H. D., Fentem, P. H., & Bassey, E. J. (1988). Falls by elderly people at home: Prevalence and associated factors. Age and Ageing, 17(6), 365–372. https://doi.org/10.1093/AGEING/17.6.365

Borrelli, B., Sepinwall, D., Bellg, A. J., Breger, R., DeFrancesco, C., Sharp, D. L., Ernst, D., Czajkowski, S., Levesque, C., Ogedegbe, G., Resnick, B., & Orwig, D. (2005). A new tool to assess treatment fidelity and evaluation of treatment fidelity across 10 years of health behavior research. Journal of Consulting and Clinical Psychology, 73(5), 852–860. https://doi.org/10.1037/0022-006X.73.5.852

Brooks, J., McCluskey, S., Turley, E., & King, N. (2015). The utility of template analysis in qualitative psychology research. Qualitative Research in Psychology, 12(2), 202–222. https://doi.org/10.1080/14780887.2014.955224

Burns, E., Kakara, R., & Moreland, B. (2023). A CDC compendium of effective fall interventions: What works for community-dwelling older adults (4th ed.). Centers for Disease Control and Prevention, National Center for Injury Prevention and Control

Carr, J., & Shepherd, R. (1998). *Neurological Rehabilitation: Optimizing Motor Performance - Janet H. Carr, Roberta B. Shepherd*. Elsevier Health Sciences. https://books.google.com/books?hl=en&lr=&id=19pfDwAAQBAJ&oi=fnd&pg=PP1&dq=Carr+JH+and+Shepherd+R+(1998):+Neurological+Rehabilitation:+Optimizing+Motor+Performance.+Oxford:+Butterworth+Heinemann,+pp.154-181.&ots=KFZdA8L2GF&sig=4VutJaZkZ9NW7aLYGmmMAeHZwbg#v=onepage&q&f=false

Carty, C. P., Barrett, R. S., Cronin, N. J., Lichtwark, G. A., Mills, P. M., & Ferrucci, L. (2012). Lower Limb Muscle Weakness Predicts Use of a Multiple- Versus Single-Step Strategy to Recover From Forward Loss of Balance in Older Adults. *The Journals of Gerontology: Series A*, *67*(11), 1246–1252. https://doi.org/10.1093/GERONA/GLS149

Carty, C. P., Cronin, N. J., Lichtwark, G. A., Mills, P. M., & Barrett, R. S. (2012). Mechanisms of adaptation from a multiple to a single step recovery strategy following repeated exposure to forward loss of balance in older adults. *PLoS ONE*, *7*(3). https://doi.org/10.1371/journal.pone.0033591

Carty, C. P., Cronin, N. J., Nicholson, D., Lichtwark, G. A., Mills, P. M., Kerr, G., Cresswell, A. G., & Barrett, R. S. (2015). Reactive stepping behaviour in response to forward loss of balance predicts future falls in community-dwelling older adults. *Age and Ageing*, *44*(1), 109–115. https://doi.org/10.1093/ageing/afu054

Carty, C. P., Mills, P., & Barrett, R. (2011). Recovery from forward loss of balance in young and older adults using the stepping strategy. *Gait and Posture*. https://doi.org/10.1016/j.gaitpost.2010.11.017

Centers for Disease Control and Prevention, N. C. for H. Statistics. N. V. S. System. (2021). *Mortality 1999–2020 on CDC WONDER Online Database, released in 2021.* https://wonder.cdc.gov/ucd-icd10.html

Chan, B. K. S., Marshall, L. M., Winters, K. M., Faulkner, K. A., Schwartz, A. V., & Orwoll, E. S. (2007). Incident Fall Risk and Physical Activity and Physical Performance among Older MenThe Osteoporotic Fractures in Men Study. *American Journal of Epidemiology*, *165*(6), 696–703. https://doi.org/10.1093/AJE/KWK050

Chang, V.C., & Do, M.T. (2015). Risk factors for falls among seniors: Implications of gender. American Journal of Epidemiology, 181(7), 521–531. https://doi.org/10.1093/AJE/KWU268

Chodzko-Zajko, W., Proctor, D., Fiatarone Singh, M., Minson, C., Nigg, C., Salem, G., & Skinner, J. (2009). Exercise and Physical Activity for Older Adults SUMMARY. *Medicine & Science in Sports & Exercise*, *41*(7), 1510–1530. https://doi.org/10.1249/MSS.0b013e3181a0c95c

Cronin, N. J., Barrett, R. S., Lichtwark, G., Mills, P. M., & Carty, C. P. (2013). Decreased lower limb muscle recruitment contributes to the inability of older adults to recover with a single step following a forward loss of balance. *Journal of Electromyography and Kinesiology*, *23*(5), 1139–1144. https://doi.org/10.1016/J.JELEKIN.2013.05.012

Daubney, M. E., & Culham, E. G. (1999). Lower-Extremity Muscle Force and Balance Performance in Adults Aged 65 Years and Older. *Physical Therapy*, *79*(12), 1177–1185. https://doi.org/10.1093/PTJ/79.12.1177

Delbaere, K., Gschwind, Y. J., Sherrington, C., Barraclough, E., Garrués-Irisarri, M. A., & Lord, S. R. (2016). Validity and reliability of a simple 'low-tech' test for measuring choice stepping reaction time in older people Article. *Clinical Rehabilitation*, *30*(11), 1128–1135. https://doi.org/10.1177/0269215515613422

Dempster, W. (1955). Space requirements of the seated operator. Wright Patterson Air Force Base.

Devasahayam, A. J., Farwell, K., Lim, B., Morton, A., Fleming, N., Jagroop, D., Aryan, R., Saumur, T. M., & Mansfield, A. (2022). The effect of reactive balance training on falls in daily life: An updated systematic review and meta-analysis. Physical Therapy, 103(1), pzac154. https://doi.org/10.1093/PTJ/PZAC154

Dipietro, L., Campbell, W. W., Buchner, D. M., Erickson, K. I., Powell, K. E., Bloodgood, B., Hughes, T., Day, K. R., Piercy, K. L., Vaux-Bjerke, A., & Olson, R. D. (2019). Physical Activity, Injurious Falls, and Physical Function in Aging: An Umbrella Review. In *Medicine and Science in Sports and Exercise* (Vol. 51, Issue 6, pp. 1303–1313). Lippincott Williams and Wilkins. https://doi.org/10.1249/MSS.0000000000001942

Dykes, P. C., Curtin-Bowen, M., Lipsitz, S., Franz, C., Adelman, J., Adkison, L., Bogaisky, M., Carroll, D., Carter, E., Herlihy, L., Lindros, M. E., Ryan, V., Scanlan, M., Walsh, M. A., Wien, M., & Bates, D. W. (2023). Cost of Inpatient Falls and Cost-Benefit Analysis of Implementation of an Evidence-Based Fall Prevention Program. *JAMA Health Forum*, *4*(1), e225125. https://doi.org/10.1001/JAMAHEALTHFORUM.2022.5125

Enderlin, C., Rooker, J., Ball, S., Hippensteel, D., Alderman, J., Fisher, S. J., McLeskey, N., & Jordan, K. (2015). Summary of factors contributing to falls in older adults and nursing implications. *Geriatric Nursing*, *36*(5). https://doi.org/10.1016/j.gerinurse.2015.08.006

Extension | National Institute of Food and Agriculture. (2022). Retrieved April 8, 2023, from https://www.nifa.usda.gov/about-nifa/how-we-work/extension

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. https://doi.org/10.1111/jgs.15304

Gerards, M. H. G., 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. https://doi.org/10.1111/GGI.13082

Gerards, M. H. G., Marcellis, R. G. J., Poeze, M., Lenssen, A. F., Meijer, K., & de Bie, R. A. (2021). Perturbation-based balance training to improve balance control and reduce falls in older adults—Study protocol for a randomized controlled trial. BMC Geriatrics, 21(1), 1–12. https://doi.org/10.1186/s12877-020-01944-7

Gerards, M., Sieben, J., Marcellis, R., de Bie, R. A., Meijer, K., & Lenssen, A. F. (2022). Acceptability of a perturbation-based balance training programme for falls prevention in older adults: a qualitative study. *BMJ Open*, *12*, 56623. https://doi.org/10.1136/bmjopen-2021-056623

Gerards, M. H. G., Marcellis, R., Senden, R., Poeze, M., de Bie, R., Meijer, K., & Lenssen, A. (2023). The effect of perturbation-based balance training on balance control and fear of falling in older adults: a single-blind randomised controlled trial. BMC Geriatrics, 23(1), 305. https://doi.org/10.1186/s12877-023-03988-x

Gonthier, C., Braver, T. S., & Bugg, J. M. (2016). Dissociating proactive and reactive control in the Stroop task. *Memory and Cognition*, *44*(5), 778–788. https://doi.org/10.3758/S13421-016-0591-1/FIGURES/6

Grabiner, M. D., Donovan, S., Bareither, M., Lou, 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. https://doi.org/10.1016/j.jelekin.2007.06.009

Graham, D. F., Carty, C. P., Lloyd, D. G., & Barrett, R. S. (2015). Biomechanical predictors of maximal balance recovery performance amongst community-dwelling older adults. *Experimental Gerontology*, *66*, 39–46. https://doi.org/10.1016/j.exger.2015.04.006

Graham, D. F., Carty, C. P., Lloyd, D. G., Lichtwark, G. A., & Barrett, R. S. (2014). Muscle contributions to recovery from forward loss of balance by stepping. *Journal of Biomechanics*. https://doi.org/10.1016/j.jbiomech.2013.11.047

Granacher, U., Muehlbauer, T., & Gruber, M. (2012). A qualitative review of balance and strength performance in healthy older adults: Impact for testing and training. In *Journal of Aging Research* (Vol. 2012). https://doi.org/10.1155/2012/708905

Hall, K.S., Howe, C.A., Rana, S.R., Martin, C.L., & Morey, M.C. (2013). METs and accelerometry of walking in older adults: Standard versus measured energy cost. Medicine & Science in Sports & Exercise, 45(3), 574–582. https://doi.org/10.1249/MSS.0b013e318276c73c

Hawley-Hague, H., Boulton, E., Hall, A., Pfeiffer, K., & Todd, C. (2014). Older adults' perceptions of technologies aimed at falls prevention, detection or monitoring: A systematic review. International Journal of Medical Informatics, 83(6), 416–426. https://doi.org/10.1016/J.IJMEDINF.2014.03.002

Hayes, W. C., Myers, E. R., Morris, J. N., Gerhart, T. N., Yett, H. S., & Lipsitz, L. A. (1993). Impact near the hip dominates fracture risk in elderly nursing home residents who fall. *Calcified Tissue International*, *52*(3), 192–198. https://doi.org/10.1007/BF00298717

Hezel, N., Brüll, L., Arampatzis, A., & Schwenk, M. (2024). Acceptability of Two Perturbation-Based Balance Training Paradigms: Perturbation Treadmill versus Dynamic Stability Training in the Presence of Perturbations. *Gerontology*, *70*(6), 661–668. https://doi.org/10.1159/000538105

Hoffman, G., Franco, N., Perloff, J., Lynn, J., Okoye, S., & Min, L. (2022). Incidence of and county variation in fall injuries in US residents aged 65 years or older, 2016–2019. JAMA Network Open, 5(2), Article 48007. https://doi.org/10.1001/JAMANETWORKOPEN.2021.48007

Hommel, K. A., Hente, E., Herzer, M., Ingerski, L. M., & Denson, L. A. (2013). Telehealth behavioral treatment for medication nonadherence: A pilot and feasibility study. European Journal of Gastroenterology & Hepatology, 25(4), 469. https://doi.org/10.1097/MEG.0B013E32835C2A1B

Huxham, F. E., Goldie, P. A., & Patla, A. E. (2001). Theoretical considerations in balance assessment. *Australian Journal of Physiotherapy*, *47*(2), 89–100. https://doi.org/10.1016/S0004-9514(14)60300-7

Injury Prevention Program, M. (2021). *The Burden of Falls Among Adults in Montana*. https://dphhs.mt.gov/publichealth/EMSTS/prevention/falls

Jager, T. E., Weiss, H. B., Coben, J. H., & Pepe, P. E. (2000). Traumatic brain injuries evaluated in U.S. emergency departments, 1992- 1994. *Academic Emergency Medicine*, *7*(2), 134–140. https://doi.org/10.1111/j.1553-2712.2000.tb00515.x

James, S.L., Lucchesi, L.R., Bisignano, C., Castle, C.D., Dingels, Z.V., Fox, J.T., Hamilton, E.B., Henry, N.J., Krohn, K.J., Liu, Z., Mccracken, D., Nixon, M.R., Roberts, N.L.S., Sylte, D.O., Adsuar, J.C., Arora, A., Briggs, A.M., Collado-Mateo, D., Cooper, C.,: Murray, C.J.L. (2020). The global burden of falls: Global, regional and national estimates of morbidity and mortality from the Global Burden of Disease Study 2017. Injury Prevention, 26(Suppl. 2), i3–i11. https://doi.org/10.1136/INJURYPREV-2019-043286

Joshua Devasahayam, A., Farwell, K., Lim, B., Morton, A., Fleming, N., Jagroop, D., Aryan, R., Mitchell Saumur, T., & Mansfield, A. (2022). The Effect of Reactive Balance Training on Falls in Daily Life: An Updated Systematic Review and Meta-Analysis Does Reactive Balance Training Prevent Falls? Neurology Review. *Physical Therapy*. https://doi.org/10.1093/ptj/pzac154/6812867

Kellis, E., & Baltzopoulos, V. (1996). Gravitational moment correction in isokinetic dynamometry using anthropometric data. Medicine & Science in Sports & Exercise, 28(7), 900–907. https://doi.org/10.1097/00005768-199607000-00018

Khalaj, N., Osman, N.A.A., Mokhtar, A.H., Mehdikhani, M., & Abas, W.A.B.W. (2014). Balance and risk of fall in individuals with bilateral mild and moderate knee osteoarthritis. PLoS One, 9(3), Article 92270. https://doi.org/10.1371/JOURNAL.PONE.0092270

Kim, H. K., & Chou, L. S. (2022). Lower limb muscle activation in response to balance-perturbed tasks during walking in older adults: A systematic review. *Gait & Posture*, *93*, 166–176. https://doi.org/10.1016/J.GAITPOST.2022.02.014

Kim, Y., Vakula, M. N., Bolton, D. A. E., Dakin, C. J., Thompson, B. J., Slocum, T. A., Teramoto, M., & Bressel, E. (2022). Which Exercise Interventions Can Most Effectively Improve Reactive Balance in Older Adults? A Systematic Review and Network Meta-Analysis. *Frontiers in Aging Neuroscience*, *13*. https://doi.org/10.3389/fnagi.2021.764826

Kiss, R., Schedler, S., & Muehlbauer, T. (2018). Associations Between Types of Balance Performance in Healthy Individuals Across the Lifespan: A Systematic Review and Meta-

Analysis. In *Frontiers in Physiology* (Vol. 9). Frontiers Media S.A. https://doi.org/10.3389/fphys.2018.01366

Klenk, J., Kerse, N., Rapp, K., Nikolaus, T., Becker, C., Rothenbacher, D., Peter, R., & Denkinger, M.D. (2015). Physical activity and different concepts of fall risk estimation in older people–results of the ActiFE-Ulm study. PLoS One, 10(6), Article 129098. https://doi.org/10.1371/journal.pone.0129098

Lamb, S.E., Jørstad-Stein, E.C., Hauer, K., & Becker, C. (2005). Development of a common outcome data set for fall injury prevention trials: The prevention of falls Network Europe consensus. Journal of the American Geriatrics Society, 53(9), 1618–1622. https://doi.org/10.1111/J.1532-5415.2005.53455.X

Lee, A., Bhatt, T., Liu, X., Wang, Y., & Pai, Y. C. (2018). Can higher training practice dosage with treadmill slip-perturbation necessarily reduce risk of falls following overground slip? *Gait & Posture*, *61*, 387–392. https://doi.org/10.1016/J.GAITPOST.2018.01.037

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 (Auckland, N.Z.)*, *45*(12), 1721–1738. https://doi.org/10.1007/S40279-015-0375-Y

Lindgren De Groot, G. C., Fagerström, L., Cathrine, G., & De Groot, L. (2011). Older adults' motivating factors and barriers to exercise to prevent falls. Scandinavian Journal of Occupational Therapy, 18(2), 153–160. https://doi.org/10.3109/11038128.2010.487113

Liu, X., Bhatt, T., & Pai, Y. C. (2016). Intensity and generalization of treadmill slip training: High or low, progressive increase or decrease? *Journal of Biomechanics*, *49*(2), 135–140. https://doi.org/10.1016/j.jbiomech.2015.06.004

Lord, S.R., Menz, H.B., & Tiedemann, A. (2003). A physiological profile approach to falls risk assessment and prevention. Physical Therapy, 83(3), 237–252. https://doi.org/10.1093/ptj/83.3.237

Lurie, J. D., Zagaria, A. B., Ellis, L., Pidgeon, D., Gill-Body, K. M., Burke, C., Armbrust, K., Cass, S., Spratt, K. F., & McDonough, C. M. (2020). Surface Perturbation Training to Prevent Falls in Older Adults: A Highly Pragmatic, Randomized Controlled Trial. *Physical Therapy*, *100*(7), 1153–1162. https://doi.org/10.1093/PTJ/PZAA023

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://doi.org/10.1007/S001980070086

Madigan, M. L., & Lloyd, E. M. (2005). Age and Stepping Limb Performance Differences During a Single-Step Recovery From a Forward Fall. *The Journals of Gerontology Series*

A: Biological Sciences and Medical Sciences, *60*(4), 481–485. https://doi.org/10.1093/gerona/60.4.481

Maki, B. E., & McIlroy, W. E. (2006). Control of rapid limb movements for balance recovery: Age-related changes and implications for fall prevention. *Age and Ageing*, *35*(SUPPL.2). https://doi.org/10.1093/ageing/afl078

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., Danells, C. J., Inness, E. L., Musselman, K., & Salbach, N. M. (2021). A survey of Canadian healthcare professionals' practices regarding reactive balance training. *Physiotherapy Theory and Practice*, *37*(7), 787–800. https://doi.org/10.1080/09593985.2019.1650856

Mansfield, A., Depaul, V., Danells, C., Inness, E., Biasin, L., Poon, V., & Knorr, S. (2017). *Toronto Perturbation-Based Balance Training Program Manual Program developed and manual written by: Toronto Perturbation-Based Balance Training: Program Manual*.

Mansfield, A., Inness. L. , Danells, C. J. , Jagroop, D. , Musselman, K. E. , Salbach, N. M., & Kochanowski. (2021). *Implementing reactive balance training in rehabilitation practice: a guide for healthcare professionals*.

Mansfield, A., Inness, E. L., Danells, C. J., Jagroop, D., Bhatt, T., & Huntley, A. H. (2020). Determining the optimal dose of reactive balance training after stroke: study protocol for a pilot randomised controlled trial. *BMJ Open*, *10*(8), e038073. https://doi.org/10.1136/BMJOPEN-2020-038073

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. https://doi.org/10.2522/ptj.20140090

Margalit, N., Kurz, I., Wacht, O., Mansfield, A., & Melzer, I. (2023). A survey of Israeli physical therapists regarding reactive balance training. BMC Geriatrics, 23(1), 656. https://doi.org/10.1186/s12877-023-04356-5

Massion, J., & Woolacott, M. (1998). Posture and equilibrium. In *Clinical Disorders of Balance, Posture and Gait, 2Ed*. CRC Press. https://doi.org/10.1201/B13189-8

McCrum, C., Bhatt, T. S., Gerards, M. H. G., Karamanidis, K., Rogers, M. W., Lord, S. R., & Okubo, Y. (2022). Perturbation-based balance training: Principles, mechanisms and implementation in clinical practice. *Frontiers in Sports and Active Living*, *4*. https://doi.org/10.3389/fspor.2022.1015394

McCrum, C., Bhatt, T. S., Gerards, M. H. G., Karamanidis, K., Rogers, M. W., Lord, S. R., & Okubo, Y. (2022). Perturbation-based Balance Training: Principles, Mechanisms and Implementation in Clinical Practice. *OSF Preprints. McCrum et Al*. https://doi.org/10.31219/osf.io/u8fsb

McCrum, C., Essers, J. M. N., Jie, L.-J., Liu, W.-Y., & Meijer, K. (2016). Commentary: Older adults can improve compensatory stepping with repeated postural perturbations. *Frontiers in Aging Neuroscience*, *8*(MAY), 201. https://doi.org/10.3389/fnagi.2016.00111

McCrum, C., Gerards, M. H. G., 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. In *European Review of Aging and Physical Activity* (Vol. 14, Issue 1). Springer Verlag. https://doi.org/10.1186/s11556-017-0173-7

McCrum, C., & Okubo, Y. (2023). Editorial: Perturbation-based balance training. *Frontiers in Sports and Active Living*, *5*, 1306133. https://doi.org/10.3389/FSPOR.2023.1306133/BIBTEX

Menant, J. C., Steele, J. R., Menz, H. B., Munro, B. J., & Lord, S. R. (2009). Effects of walking surfaces and footwear on temporo-spatial gait parameters in young and older people. *Gait & Posture*, *29*(3), 392–397. https://doi.org/10.1016/J.GAITPOST.2008.10.057

Miller, C. T., Teychenne, M., & Maple, J. L. (2018). The perceived feasibility and acceptability of a conceptually challenging exercise training program in older adults. Clinical Interventions in Aging, 13, 451–461. https://doi.org/10.2147/CIA.S154664

Moreira, N. B., Rodacki, A. L. F., Pereira, G., & Bento, P. C. B. (2018). Does functional capacity, fall risk awareness and physical activity level predict falls in older adults in different age groups? *Archives of Gerontology and Geriatrics*, *77*, 57–63. https://doi.org/10.1016/j.archger.2018.04.002

NonFatal Data | WISQARS | Injury Center | CDC. (n.d.).

Okubo, Y., Seino, S., Yabushita, N., Osuka, Y., Jung, S., Nemoto, M., Figueroa, R., & Tanaka, K. (2015). Longitudinal association between habitual walking and fall occurrences among community-dwelling older adults: Analyzing the different risks of falling. Archives of Gerontology and Geriatrics, 60(1), 45–51. https://doi.org/10.1016/J.ARCHGER.2014.10.008

Okubo, Y., Osuka, Y., Jung, S., Rafael, F., Tsujimoto, T., Aiba, T., Kim, T., & Tanaka, K. (2016). Walking can be more effective than balance training in fall prevention among community-dwelling older adults. Geriatrics and Gerontology International, 16(1), 118–125. https://doi.org/10.1111/ggi.12444

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. https://doi.org/10.1136/BJSPORTS-2015-095452

O'loughlin, J. L., Robitaille, Y., Boivin, J. F., & Suissa, S. (1993). Incidence of and risk factors for falls and injurious falls among the community-dwelling elderly. *American Journal of Epidemiology*, *137*(3), 342–354. https://doi.org/10.1093/OXFORDJOURNALS.AJE.A116681

Pai, Y. C., Bhatt, T., Wang, E., Espy, D., & Pavol, M. J. (2010). Inoculation Against Falls: Rapid Adaptation by Young and Older Adults to Slips During Daily Activities. *Archives of Physical Medicine and Rehabilitation*, *91*(3), 452–459. https://doi.org/10.1016/j.apmr.2009.10.032

Pai, Y. C., Bhatt, T., Yang, F., & Wang, E. (2014). Perturbation Training Can Reduce Community-Dwelling Older Adults' Annual Fall Risk: A Randomized Controlled Trial. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *69*(12), 1586. https://doi.org/10.1093/GERONA/GLU087

Patel, P., & Bhatt, T. (2015). Adaptation to large-magnitude treadmill-based perturbations: improvements in reactive balance response. *Physiological Reports*, *3*(2), e12247. https://doi.org/10.14814/PHY2.12247

Pereira, C. L. N., Baptista, F., & Infante, P. (2013). Role of physical activity in the occurrence of falls and fall-related injuries in community-dwelling adults over 50 years old. *Disability and Rehabilitation*, *36*(2), 117–124. https://doi.org/10.3109/09638288.2013.782355

Podsiadlo, D., & Richardson, S. (1991). The timed 'Up & Go': a test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society*, *39*(2), 142–148. https://doi.org/10.1111/J.1532-5415.1991.TB01616.X

Rivera-Torres, S., Fahey, T.D., & Rivera, M.A. (2019). Adherence to exercise programs in older adults: Informative report. Gerontology & Geriatric Medicine, 5, Article 604. https://doi.org/10.1177/2333721418823604

Rubenstein, L. Z. (2006). Falls in older people: Epidemiology, risk factors and strategies for prevention. *Age and Ageing*, *35*(SUPPL.2). https://doi.org/10.1093/ageing/afl084

Salari, N., Darvishi, N., Ahmadipanah, M., Shohaimi, S., & Mohammadi, M. (2022). Global prevalence of falls in the older adults: A comprehensive systematic review and meta-analysis. Journal of Orthopaedic Surgery and Research, 17(1), Article 334. https://doi.org/10.1186/S13018-022-03222-1

Sasaki, J.E., Júnior, J.H., Meneguci, J., Tribess, S., Marocolo Júnior, M., Stabelini Neto, A., & Virtuoso Júnior, J.S. (2017). Number of days required for reliably estimating physical activity and sedentary behaviour from accelerometer data in older adults. Disability and Rehabilitation, 36(14), 1572–1577. https://doi.org/10.1080/02640414.2017.1403527

Schlenstedt, C., Paschen, S., Kruse, A., Raethjen, J., Weisser, B., & Deuschl, G. (2015). Resistance versus balance training to improve postural control in Parkinson's disease: A randomized rater blinded controlled study. *PLoS ONE*, *10*(10). https://doi.org/10.1371/journal.pone.0140584

Seidler, R. D., & Stelmach, G. E. (2012). Reduction in Sensorimotor Control With Age. *Https://Doi.Org/10.1080/00336297.1995.10484165*, *47*(3), 386–394. https://doi.org/10.1080/00336297.1995.10484165

Sekhon, M., Cartwright, M., & Francis, J. J. (2017). Acceptability of healthcare interventions: An overview of reviews and development of a theoretical framework. *BMC Health Services Research*, *17*(1). https://doi.org/10.1186/s12913-017-2031-8

Sheehan, R.C., Guerrero, N., Wilson, J.B., Zai, C.Z., Kingsbury, T.D., Tullos, M.L., Acasio, J.C., Mahon, C.E., Miller, E., Hendershot, B.D., Dearth, C.L., Grabiner, M.D., & Kaufman, K.R. (2022). Common fall-risk indicators are not associated with fall prevalence in a high-functioning military population with lower limb trauma. Clinical Biomechanics, 100, Article 105774. https://doi.org/10.1016/j.clinbiomech.2022.105774

Sherrington, C., Fairhall, N., Kwok, W., Wallbank, G., Tiedemann, A., Michaleff, Z. A., Ng, C. A. C. M., & Bauman, A. (2020). Evidence on physical activity and falls prevention for people aged 65+ years: systematic review to inform the WHO guidelines on physical activity and sedentary behaviour. *International Journal of Behavioral Nutrition and Physical Activity*, *17*(1), 1–9. https://doi.org/10.1186/S12966-020-01041-3/FIGURES/3

Sherrington, C., Whitney, J. C., Lord, S. R., Herbert, R. D., Cumming, R. G., & Close, J. C. T. (2008). Effective exercise for the prevention of falls: A systematic review and meta-analysis. *Journal of the American Geriatrics Society*, *56*(12), 2234–2243. https://doi.org/10.1111/j.1532-5415.2008.02014.x

Shumway-Cook, A., & Woollacott, M. H. (2016). *Motor Control: Translating Research Into Clinical Practice*. https://books.google.com/books?hl=en&lr=&id=BJcL3enz3xMC&oi=fnd&pg=PA1&ots=lFtiiyHSsR&sig=o2dGcSMb7ZQEpPOL2qZ49g5JfAE#v=onepage&q&f=false

Smania, N., Corato, E., Tinazzi, M., Stanzani, C., Fiaschi, A., Girardi, P., & Gandolfi, M. (2010). Effect of balance training on postural instability in patients with idiopathic parkinson's disease. *Neurorehabilitation and Neural Repair*, *24*(9), 826–834. https://doi.org/10.1177/1545968310376057

Smith, T.O., Higson, E., Pearson, M., & Mans eld, M. (2018). Is there an increased risk of falls and fractures in people with early diagnosed hip and knee osteoarthritis? Data from the Osteoarthritis Initiative. International Journal of Rheumatic Diseases, 21(6), 1193–1201. https://doi.org/10.1111/1756-185X.12871

Stelmach, G. E., & Worringham, C. J. (1985). Sensorimotor Deficits Related to Postural Stability: Implications for Falling in the Elderly. *Clinics in Geriatric Medicine*, *1*(3), 679–694. https://doi.org/10.1016/S0749-0690(18)30933-9

Syddall, H. E., Martin, H. J., Harwood, R. H., Cooper, C., & Aihie Sayer, A. (2009). The SF-36: A simple, effective measure of mobility-disability for epidemiological studies. *The Journal of Nutrition, Health & Aging*, *13*(1), 57–62.

Sylliaas, H., Idland, G., Sandvik, L., Forsen, L., & Bergland, A. (2009). Does mortality of the aged increase with the number of falls? Results from a nine-year follow-up study. *European Journal of Epidemiology*, *24*(7), 351–355. https://doi.org/10.1007/S10654-009-9348-5/TABLES/2

Talbot, L. A., Musiol, R. J., Witham, E. K., & Metter, E. J. (2005). Falls in young, middle-aged and older community dwelling adults: Perceived cause, environmental factors and injury. BMC Public Health, 5, 1–9. https://doi.org/10.1186/1471-2458-5-86

Tinetti, M.E., & Kumar, C. (2010). The patient who falls:“It’s always a trade-off.” The Journal of the American Medical Association, 303(3), Article 258. https://doi.org/10.1001/JAMA.2009.2024

Tombaugh, T. N., & McIntyre, N. J. (1992). The mini-mental state examination: A comprehensive review. Journal of the American Geriatrics Society, 40(9), 922–935. https://doi.org/10.1111/J.1532-5415.1992.TB01992.X

Troiano, R.P., Berrigan, D., Dodd, K.W., Mâsse, L.C., Tilert, T., & Mcdowell, M. (2008). Physical activity in the United States measured by accelerometer. Medicine & Science in Sports & Exercise, 40(1), 181–188. https://doi.org/10.1249/MSS.0B013E31815A51B3

Tsonga, T., Michalopoulou, M., Malliou, P., Godolias, G., Kapetanakis, S., Gkasdaris, G., & Soucacos, P. (2015). Analyzing the history of falls in patients with severe knee osteoarthritis. Clinics in Orthopedic Surgery, 7(4), 449–456. https://doi.org/10.4055/CIOS.2015.7.4.449

Unger, J., Chan, K., Lee, J. W., Craven, B. C., Mansfield, A., Alavinia, M., Masani, K., & Musselman, K. E. (2021). The Effect of Perturbation-Based Balance Training and

Conventional Intensive Balance Training on Reactive Stepping Ability in Individuals With Incomplete Spinal Cord Injury or Disease: A Randomized Clinical Trial. *Frontiers in Neurology*, *12*, 49. https://doi.org/10.3389/FNEUR.2021.620367/BIBTEX

US Census Bureau. (2024, April). *Older Population and Aging*. https://www.census.gov/topics/population/older-aging.html

US Department of Health and Human Services. (n.d.). *Physical Activity Guidelines for Americans 2nd edition*.

Wang, Y., Wang, S., Lee, A., Pai, Y. C., & Bhatt, T. (2019). Treadmill-gait slip training in community-dwelling older adults: Mechanisms of immediate adaptation for a progressive ascending-mixed-intensity protocol. Experimental Brain Research, 237, 2305–2317.

Whitten, J., Tarabochia, D., MacDonald, D., Barrett, R., Carty, C., & Graham, D. (2021). The relationship between physical activity intensity and volume on prospective falls in older adults. *Innovation in Aging*, *5*(Supplement_1), 687–688. https://doi.org/10.1093/GERONI/IGAB046.2563

Yardley, L., Donovan-Hall, M., Francis, K., & Todd, C. (2007). Attitudes and beliefs that predict older people's intention to undertake strength and balance training. The Journals of Gerontology: Series B, 62(2), P119–P125. https://doi.org/10.1093/GERONB/62.2.P119

Yang, & Hannah. (2021). *Montana Trauma Registry Annual Report 2021*.

Yungher, D. A., Morgia, J., Bair, W. N., Inacio, M., Beamer, B. A., Prettyman, M. G., & Rogers, M. W. (2012). Short-term changes in protective stepping for lateral balance recovery in older adults. *Clinical Biomechanics*, *27*(2), 151–157. https://doi.org/10.1016/j.clinbiomech.2011.09.003