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Falling poses a significant risk of injury for older adults, thus decreasing quality of life. Major risk factors for falling include decrements in gait and balance, and adverse patient-reported health and well-being. Virtual Reality (VR) can be a cost-effective, resource-efficient, and highly engaging training tool, and previous research has utilized VR to reduce fall-risk factors in a variety of populations with aging and pathology. However, there are barriers to implementing VR as a training tool to improve functional mobility in older adults that include the manner in which healthy older adults perform in VR relative to younger adults, the effect of extended duration training, and the relation of fall-risk clinical metrics to performance in VR. The purpose of this dissertation is three-fold: (1) to compare performance between older and younger adults in VR and in real-world gait and balance tests as a result of a single bout of VR training; (2) to compare performance in VR and gait and balance within younger adults as a result of extended training duration; and (3) to evaluate clinical tests as prerequisite measures for performance within the VR environment. Thirty-five healthy adults participated in this study and were placed into either the older adult training group (n=8; 67.0±4.4yrs), younger training (n=13; 22.1±2.5yrs), or younger control (n=13; 21.7±1.0yrs). All participants completed an online patient-reported survey of balance confidence and health and well-being, as well as a pre-test of clinical assessments and walking and balance tests. The training groups then completed 15 trials of a VR obstacle course, while the controls walked overground for 15 minutes. The VR obstacle course included a series of gait and dynamic balance tasks, such as stepping on irregularly placed virtual stepping stones and walking a virtual balance beam. All participants repeated the walking and balance tests at post-test. The younger training group also completed 3 weeks of training in the same VR obstacle course and a second post-test. Analyses of variance were completed to determine the extent to which participants improved within VR and the walking and balance tests both as a result of a single bout of training, and for the younger adults – three weeks of extended training. Multiple regressions were run to determine the extent to which patient-reports and clinical assessments may predict performance within VR. The results reported in Manuscript I show that although younger adults completed the VR course quicker, their learning rate was not different from older adults; and as a result of extended training, younger adults continued to improve their time to complete the course. For gait and balance tests, age related differences were observed. Both groups showed better performance on some post-tests, indicating that VR training may have had a positive effect on neuromotor control. The results reported in Manuscript II suggest the RAND-1 pain subscale and simple reaction time (SRT) may predict time to complete the VR course, and SRT and BBS Q14 may additionally predict obstacle contact. These data suggest a VR obstacle course may be effective in improving gait and balance in both younger and older adults. It is recommended that future work enroll older adults in the extended training portion of the study and to increase the VR obstacle course difficulty when benchmarks are met.

TRAINING FUNCTIONAL MOBILTY USING A DYNAMIC VIRTUAL REALITY OBSTACLE COURSE

by

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CHAPTER I

INTRODUCTION

Falling significantly decreases quality of life for older adults and increases chance of morbidity. Approximately 25% of older adults (age ≥ 65 years) fall each year (Bergen et al., 2016), placing them at significant risk of injury, such as broken bones or head trauma (Alexander et al., 1992; Sterling et al., 2001), and hospital stays, thus putting a strain on our health care system. Fall injuries typically lead to a reduction in physical capability, consequently decreasing mobility and physical activity (Rubenstein, 2006) and increasing fear of falling and lack of confidence in executing activities of daily living (Li et al., 2003; Rubenstein, 2006; Tinetti et al., 1988). Ultimately, this leads to reliance on a caretaker or family member (Kuzuya et al., 2006; Sattin et al., 1990) and a higher risk of adverse long-term health-related outcomes (King & Tinetti, 1995).

Risk factors for falling are numerous and may be related to physiological changes due to aging or as a consequence of the natural environment a person is in. The most common risk factors for falling are related to gait and balance and are a result of the adoption of inappropriate neuromuscular control strategies with respect to poorer adaptive gait responses in terms of increased stride variability (Maki, 2015), loss of stride interval complexity (Lipsitz, 2002, 2004), decreased gait speed, step length, and step width, and poor adaptations to obstacle perturbation (Berg, Alessio, Mills, & Tong, 1997; Chen, Ashton-Miller, Alexander, & Schultz, 1991, 1994; Muir, Haddad, Heijnen, &

Rietdyk, 2015). Additionally poorer postural control and balance affect neuromuscular control as indicated by larger amplitudes of CoP displacement in the mediolateral direction (Maki et al., 1994; Swanenburg et al., 2010) and increased velocity in the anteroposterior direction (Berg et al., 1992).

Fall-risk factors in older adults are not only tied to decrements in neuromuscular control, but also to how they perceive their own health and well-being. Patient reported outcomes are indicative of their thoughts towards their own capabilities. Physical and mental health-related quality of life, as measured by the SF-36 patient survey, is associated with fall-related self-efficacy, fear of falling, and ability to perform activities of daily living (Cumming et al., 2000). Confidence in completing balance-challenging activities of daily living, as measured by the Activities of Balance Confidence Scale patient survey, is associated with physical functioning (Myers et al., 1998), balance impairment (Cho, Scarpace, & Alexander, 2004), and is the most predictive of falling in older adults (Landers et al., 2016).

However, it remains unclear how to best modify fall-risk factors related to gait, balance, and patient reported outcomes, to ultimately decrease risk of falling. Previous fall prevention programs have taken many approaches, such as multifactorial, exercise, and vitamin D supplementation, with such approaches moderately effective in producing benefits for participants (Chase et al., 2012; Guirguis-Blake et al., 2018). Nevertheless, there are barriers—including financial, resource, and social constraints—that may negatively affect implementation of these programs (Child et al., 2012; McMahon et al., 2018; Shier et al., 2016).

Virtual reality (VR) may provide unique opportunities to provide motivational training in novel and individualized ways, which could lead to greater efficacy in fall prevention. VR can be cost-effective, resource-efficient, and highly engaging, making it a very plausible means of not only rehabilitation, but as a potential tool in the design of a fall prevention program targeting gait and balance risk factors. A variety of populations with aging and disease have benefitted from gait and balance training with VR components, such as patients with Parkinson's, multiple sclerosis, acute and chronic post-stroke hemiplegia, traumatic brain injury, and cerebral palsy (Cano Porras et al., 2018). Training with VR components has also shown improvements in balance, gait spatiotemporal measures, and kinematics (Baram & Miller, 2006; Cano Porras et al., 2018; K. Cho et al., 2012; Darter & Wilken, 2011; Gates, Darter, et al., 2012; Jaffe et al., 2004; A. Lee et al., 2014; Liao et al., 2015; LoJacono et al., 2018; Mirelman et al., 2011, 2016b; Shema et al., 2014a; Sin & Lee, 2013), as well as improvements in clinical tests (Cano Porras et al., 2018). Lastly, VR is advantageous for learning motor skills as it provides task-specific information, augmented feedback, and repetition (Wulf, 2007), while ultimately keeping participants motivated and cognitively engaged in the task at hand (Cano Porras et al., 2018; Howard, 2017)

Our previous research has examined changes in performance during a non-immersive VR obstacle crossing task on a treadmill and resulting changes in real-world obstacle crossing strategies in order to understand the application of motor learning principles (skill acquisition, transfer, and retention) within VR. Our findings indicated that virtual obstacle crossing performance improved and was transferred to the real-world in the form of a safer obstacle crossing strategy in terms of an earlier initiation of crossing and an increased clearance over the obstacle (LoJacono et al., 2018). Additionally, after 48 hours, foot clearance remained elevated indicating that VR training is capable of producing more permanent changes in the real-world (LoJacono et al., 2017). These results are consistent with previous research utilizing non-immersive VR training on a treadmill with older adults (Mirelman et al., 2011, 2016b; Shema et al., 2014a) which showed improvements in spatiotemporal and obstacle crossing metrics after VR training with older adults with pathologies.

While there is evidence to support the utility of VR to enhance gait and balance, a few gaps in the literature remain that were addressed with this dissertation. First, there is a lack of normative data from healthy older adults without physical and neurological impairments on the effect of utilizing VR training in this population. This currently limits VR training as a rehabilitation tool and does not indicate the potential for VR to be used a preventative tool for those who are physically and cognitively healthy. Second, previous studies have been limited to non-immersive VR environments constrained to treadmills. This limits interaction with the virtual environment to the vertical and anteroposterior directions, as such the mediolateral direction as an avoidance strategy commonly used in our everyday natural environment is missing within VR training. Additionally, the treadmill poses time constraints and limits participants' ability to execute avoidance strategies accurately. It remains unknown how younger and older adult will respond to and perform within an overground virtual obstacle course via an immersive head-mounted display. Third, it is unknown the extent to which a longer duration of training may subsequently affect performance within the VR environment and the transfer to and improvement of real-world gait and balance. It is crucial to examine the effect of training duration to determine the extent to which gait and balance may be improved and if a ceiling effect occurs. Lastly, many clinical assessments are used to predict risk of falling via assessment of physical functioning and capability, but it remains unknown if these metrics may also be used to predict performance within the immersive overground VR environment which requires a specific amount of confidence and general ability to adapt gait and maintain balance.

To close these gaps, a series of experiments are presented in two manuscripts. The aims and associated hypotheses for each manuscript are presented below:

Manuscript I

- Experiment 1
    - Aim 1: Compare performance between older and younger adults in VR.
        - Hypothesis 1: Compared to the younger adult training group, the older adult training group would show smaller and slower performance improvement in earlier in training,
    - Aim 2: Examine the extent to which older adults improve in real-world gait and balance after a single bout of VR training compared to younger adults.
        - Hypothesis 2: The older adult training group would show a larger improvement in gait and balance tests from pre- to post-training testing compared to the younger adult training group

    - Aim 3: Examine the effect of training on real-world gait and balance within younger adults.
        - Hypothesis 3: Compared to the younger adult control group, the younger adult training group would show further improvements in real-world gait and balance tests.
- Experiment 2
    - Aim 4: Compare performance in VR with younger adults as a result of extended training duration.
        - Hypothesis 4: The younger adult training group would show improvements in performance within the VR environment in terms of decreased number of obstacles hit and decreased time to complete the course.
    - Aim 5: Compare Gait and Balance with Younger Adults as a Result of Extended Training Duration
        - Hypothesis 5: The younger adult training group would show a further improvement in real-world gait and balance tests after 3 weeks of training from day 1 post-testing to day 9 post-testing.

Manuscript II

    - Aim 1: Evaluate patient-reports and clinical tests as pre-requisite measures for performance within an overground VR obstacle course environment.

- Hypothesis 1: ABC Score, RAND-1 subscales, FGA score, simple reaction time, and BBS Q14 would be significant predictors of performance within the VR obstacle course

CHAPTER II

REVIEW OF THE LITERATURE

Overview

This literature review will discuss the public health concern of falling within older adults, proceeded by information on how gait is exhibited normally when unperturbed and how dynamical systems theory, obstacle crossing, and utilization of visual information give insights into adaptive gait. Next, this literature review will discuss the risk factors that lead to falls with a specific emphasis on factors related to gait and balance. Subsequently, measurements of gait and balance will be discussed as well as patient-reported outcomes of gait and balance capability and health and well-being. Then, virtual reality will be discussed as a potential fall prevention tool with specific reference to motor learning and the application of motor learning principles in virtual reality. Finally, a discussion of the previous research and gaps in the literature with regards to this dissertation will be presented.

Falls in Older Adults

Falls are of an increasing public health concern as they continue to significantly decrease quality of life for older adults. Approximately 25% of older adults (age ≥ 65 years) fall each year (Bergen et al., 2016). Falls place older adults at a significant risk of injury (Tinetti et al., 1988). Approximately 30-55% of injuries are minor, 4-6% result in bone fractures, and 2-10% of injuries are characterized as major thus requiring hospital stay (King & Tinetti, 1995). Over 800,000 older adults each year are hospitalized due to a fall injury (Bergen et al., 2016), thus putting a strain on our healthcare system. Most commonly, major fall injuries result in head trauma or broken bones (Alexander et al., 1992; Sterling et al., 2001). Fall injuries result in physical impairment, leading to decreased mobility, and thus decreased physical activity (Rubenstein, 2006). In rarer circumstances, approximately 2.2% of falls are fatal due to major injuries such as head injury, pulmonary embolism, etc. (King & Tinetti, 1995; Rubenstein, 2006).

In addition to injury and morbidity, falls lead to a decrease in ability to live independently without a family member or caretaker (Kuzuya et al., 2006; Sattin et al., 1990). Further, older adults who have previously fallen have an increased fear of falling (Rubenstein, 2006; Tinetti et al., 1988) and lack confidence in their ability to execute activities of daily living (Li et al., 2003). Once an older adult experiences a fall, their chance of falling again doubles (O'Loughlin et al., 1993), leading to a higher risk of adverse long-term health-related outcomes (King & Tinetti, 1995). Repeat fallers are typically older, have more difficulty with instrumental activities of daily living (IADLs) and one or more activities of daily living (ADLs), and report poorer health than non-fallers (King & Tinetti, 1995). Older adults who experience multiple falls indicate other underlying factors such as chronic disease, functional disability, etc., that may further increase risk of falling (King & Tinetti, 1995).

Factors that contribute to the risk of falling are numerous and often interrelated. Fall-risk factors are most often categorized as intrinsic or extrinsic. Intrinsic risk factors are related to physiological changes due to aging (Lajoie & Gallagher, 2004), such as medication use (Haddad, Bergen, & Luo, 2018), visual impairment (Ambrose et al., 2013), cognitive impairment (Muir, Gopaul, & Montero Odasso, 2012), and neurological and musculoskeletal disability/dysfunction (Berg et al., 1992; Tinetti, Speechley, & Ginter, 1988). Extrinsic risk factors are directly related to one's environment (Lajoie & Gallagher, 2004), such as hazardous objects, stairs, and snow/ice (Berg, Alessio, Mills, & Tong, 1997; Tinetti et al., 1988). Intrinsic and extrinsic risk factors are often interrelated. For example, fall risk associated with extrinsic factors, such as navigating an object within the gait path, is directly related to the physical capability of older adults (Rubenstein, 2006), which can be affected by fear of falling (Maki et al., 1991) and decreased physical activity/mobility (King & Tinetti, 1995), all of which are intrinsic factors. It also has been established that with an increase in number of risk factors an individual possesses, fall risk linearly increases in response (Tinetti et al., 1988), thus modifying even just a few factors could reduce fall risk.

The most prevalent fall-risk factors relate to gait, balance, and mobility. Approximately 55% falls are due to slips, trips, and displaced center of gravity while 31% due to poor mobility, balance, cognition, or sensory impairment (King & Tinetti, 1995). Furthermore, 34% of falls in older adults occur as a result of a trip with the majority of these falls occurring during obstacle traverse (Berg, Alessio, Mills, & Tong, 1997). Related to both gait and balance, older adults have a decreased ability to control their balance and walking (Maki et al., 1994; Rubenstein, 2006; Tinetti et al., 1988) due to age-related changes in reaction time (Lajoie & Gallagher, 2004), muscle mass/strength (Goodpaster et al., 2006; Tinetti & Kumar, 2010), and attention/cognitive ability

(Mirelman et al., 2012). Additionally, medication use largely affects the ability of an older adult to respond to gait and balance perturbations. Thus, examining gait, balance, and mobility factors may give an insight into fall risk, and positively modifying these factors may help reduce falling in older adults.

The Gait Cycle in Healthy Adults

Gait is perhaps the most important everyday task for human independence. The human body is an inherently unstable system, as it is shaped like an inverted pendulum with approximately two-thirds of the body mass located between the head and the hips of body (Winter, 1995). Gait is a locomotion that is cyclical and periodic in nature with the alternation between stance and swing phases of each lower extremity limb (Vaughan et al., 1999). Within the gait cycle, there are two periods of single support phase (one for each lower extremity limb) and two periods of double-support phase (Winter, 2009). A full gait cycle occurs between heel strike to following heel strike of the same limb (Robertson et al., 2004), during which the sequence of the gait cycle includes: heel-strike of the ipsilateral limb, to single support stance of the ipsilateral limb and swing of the contralateral limb, to double-support phase, to single support stance of the contralateral limb and swing of the ipsilateral limb, to following heel-strike of the ipsilateral limb. Each period of single support represents approximately 40% of the gait cycle, with the final 20% representing two periods of double support phase in which neither foot is fully flat on the ground, but supporting the mass of the body in some manner (Winter, 2009).

Gait is initiated by accelerating the center of mass forward and towards the stance limb via increased swing limb ground reaction force. The swing limb is then accelerated upwards and forwards via the hip flexors and knee extensors. The center of mass is continued in its forward acceleration via the stance limb plantarflexors and medially towards the swing limb via the hip abductors. The swing limb makes heel contact and the center of mass shifts towards the now stance limb as the cycle repeats (Winter, 2009). In order to change the direction of walking, stance-phase duration increases in order to increase step duration, allowing for greater time to modulate the impulse of the stance limb and trajectory of the swing limb to safely alter locomotion (Patla et al., 1991). Gait is terminated when the center of mass is decelerated via a rapid forward shift in the center of pressure, accomplished by increasing plantarflexion activity of the center-of-mass-accepting stance limb. Additionally, the hip abductors increase in activity to slow the lateral progression of the center of mass during this time (Winter, 2009).

There are five main functions that the lower-extremity of the body must execute to achieve safe and efficient locomotion: (1) maintenance of support of the upper body during stance, (2) maintenance of upright posture and balance of the total body, (3) control of foot trajectory to achieve safe ground clearance and a gentle heel or toe landing, (4) generation of mechanical energy to maintain the present forward velocity or to increase the forward velocity, and (5) absorption of mechanical energy for shock absorption and stability or to decrease the forward velocity of the body (Winter, 1991). Gait control improves from infancy throughout childhood and adolescence until it reaches full maturity in early adulthood. Aging alters the ability to successfully control gait to negotiate environmental hazards as the nervous and muscular systems naturally degrade. Some insights into gait control may be explained through the application of dynamical systems theory.

Dynamical Systems Theory for Adaptive Gait

Dynamical systems theory has been described as “biological systems [that] self-organize according to environmental, biomechanical, and morphological constraints to find the most stable solution for producing a given movement” (Stergiou & Decker, 2011, p. 870). Gait, although commonly considered a steady state task, contains underlying dynamic fluctuations reflecting responses to internal and external perturbations (L.A. Lipsitz, 2002) and self-organizes to continually provide the most stable solution for navigating within our environment. These dynamic fluctuations are nonlinear in nature and as such, the desire to create nonlinear analyses of gait have become more prevalent to distinguish healthy function from disease or to predict the onset of adverse health-related events (Goldberger, 1996). Measures have been derived from dynamical systems theory and nonlinear dynamics that are based on the concept of fractals, which is a geometric object or temporal feature with self-similarity over multiple measurement scales (Goldberger, 1996). Nonlinear analyses have provided new insights into how systems maintain pattern stability, transition to new states, and are governed by short-and long-term (fractal) correlational variability, stability, complexity, and adaptability. Two common nonlinear metrics for assessing gait include approximate entropy (ApEn) and detrended fluctuation analysis (DFA), which measure the structure, or organization of fluctuations, within a time series. ApEn quantifies the regularity of a time series (Pincus, 1991), while DFA quantifies the presence of long-range correlations in a time series (Hausdorff, Peng, Ladin, Wei, & Goldberger, 1995; Peng et al., 1992; Peng, Havlin, Stanley, & Goldberger, 1995).

When examining stride variability using DFA, fractal patterns emerge which may be persistent or random, or some combination of both. Persistent fluctuation refers to structured temporal fluctuations that have strong long-range correlations, while random fluctuation refers to unstructured temporal fluctuations that have weak long-range correlations (Rhea, Kiefer, D'Andrea, et al., 2014). Persistent fluctuations in gait are rigid and predictable, showing similarities to a walking robot. Conversely, random fluctuations are more noisy and unpredictable and are similar to a baby learning to walk or a drunken sailor (Stergiou & Decker, 2011). Fractal patterns, and the associated variability, may be thought of as a continuum with randomness on one side and persistence on the other. However, in the middle of this continuum is a semblance of a chaotic structure termed "optimal variability" in which a shift towards either randomness or persistence results in a loss of adaptability to perturbations and exhibit a lack of health and increased risk of falling (Stergiou & Decker).

Aging and disease negatively alters gait variability, leading to decrements in functional mobility. Stride-to-stride variability, in terms of the coefficient of variation, increases with aging and after the onset of disease, such as Huntington's or Parkinson's (Hausdorff et al., 1998), as well as in those who fall (Hausdorff, 2007) and have higher level gait disorders (Herman et al., 2005). Decrements in the structure of variability may also be observed in populations with aging and/or pathology. When compared to the DFA α of 0.75 typically exhibited by young healthy adults, older adults typically exhibit a DFA α closer to 0.5, indicating more white noise, randomness, and lack of long-range correlational structure (Hausdorff et al., 1997). Patients with higher level gait disorders—i.e., Parkinson's disease, Huntington's disease, and Amyotrophic Lateral Sclerosis—also exhibit lower DFA α values compared to healthy adults (Hausdorff et al., 1997, 2000; Herman et al., 2005). In patients with Huntington's disease, DFA α further declines as severity of the disease increases (Hausdorff et al., 1997).

Some research studies have trained individuals to exhibit a more random or more persistent fractal pattern of gait. Specifically, fractality can be altered via synchronization to a fractal stimulus to influence the timing of steps, while synchronization can be accomplished through an auditory stimulus. Previous work has shown that fractality in gait is modifiable in older adults (Kaipust et al., 2013), those with Parkinson's (Hove et al., 2012; Uchitomi et al., 2013), and healthy young adults (Marmelat et al., 2014; Rhea, Kiefer, D'Andrea, et al., 2014; Rhea, Kiefer, Wittstein, et al., 2014; Roerdink et al., 2015; Wittstein et al., 2018).

Obstacle Avoidance as an Insight into Adaptive Gait

Avoiding obstacles is crucial to safe ambulation in our everyday physical environment. Successful obstacle negotiation requires adaptations of current gait pattern and trajectory to successfully navigate over or around a potential hazard while maintaining upright stability of the body. As such, the examination of obstacle crossing strategies provides unique insight into adaptive gait. Obstacles may be stationary or dynamic in nature. Stationary obstacles allow for a slow and early adaptation of gait, such as door entryways, curbs, debris, and puddles. On the other hand, dynamic obstacles require a unexpected adaptations, such as a ball or an animal running into the gait path. Obstacles may also be perceived objects (i.e. visually stimulated), such as a shadow, glare, or virtual object, which initiate an avoidance strategy.

In order to analyze obstacle crossing strategies, foot elevation and foot placement are most commonly utilized to understand execution. Foot elevation may refer to overall vertical displacement from the ground and clearance over an obstacle. When walking unperturbed on level ground, the vertical displacements of each foot are similar between subsequent strides (Winter, 1991), albeit different for each portion of the foot. The heel of the foot achieves its single highest peak elevation just after toe-off at the beginning of swing phase (Winter, 1991). In contrast, the toe of the foot achieves two peak elevations: one that occurs shortly after toe-off and the other at heel contact during the same swing phase (Winter, 1991). When crossing an obstacle, the peak elevations of the toe and heel change to represent one large vertical displacement each over the obstacle within the swing limb trajectory, congruent with an overall increase in foot elevation as a result of obstacle crossing. Increased foot clearance over the obstacle is a result of large increases in knee and hip joint flexion of the swing limb (Patla et al., 1996; Patla & Rietdyk, 1993).

Foot placement has been suggested as a control strategy for obstacle negotiation. Examining across multiple obstacle crossings, trail foot placement before the obstacle is consistent to allow for both space and time for the trail foot to modulate trajectory and successfully clear the obstacle (Muir, Haddad, Heijnen, & Rietdyk, 2015). Obstacle contact has been associated with trail foot placement (Chou & Draganich, 1998; Patla & Greig, 2006), as decreases in distance between the trail foot and the obstacle have been associated with increases in trail foot obstacle contact (Chou & Draganich, 1998), potentially due to the decreased space and time to modulate the foot before reaching the obstacle. However, in light of this information, we must also consider the effect of visual input. The obstacle remains in the field of view during lead limb crossing and as such, the lead foot may receive online visual guidance during crossing. In contrast, the trail limb cannot be visually guided online as the trail limb is positioned behind the body during crossing (Patla et al., 1996). Therefore, successful and accurate foot placement is crucial to prevent obstacle contact and the related potential for a trip or fall. If an individual places their foot closer to the obstacle before crossing, the chance of contacting the anterior side with the toe of the foot increases and the chance of tripping subsequently increases. If an individual places their foot closer to the obstacle after crossing, the chance of stepping on the obstacle increases and the chance of slipping increases.

Successful obstacle avoidance is dependent on online modification of limb trajectory (Patla, Prentice, Robinson, & Neufeld, 1991). Injury, aging, and pathology may decrease the ability to successfully modify limb trajectory and subsequent potential for obstacle contact. After obstacle contact, an individual's gait pattern is subsequently adapted to prevent future obstacle contact (Rhea & Rietdyk, 2011). Healthy able-bodied individuals contact 1-2% of obstacles (LoJacono et al., 2018; Rhea & Rietdyk, 2007; Rietdyk & Rhea, 2006) with 67-100% of the contacts due to trail foot contact (Heijnen et al., 2014; LoJacono et al., 2018; Mohagheghi et al., 2004; Rhea & Rietdyk, 2007, 2011, 2011; Rietdyk & Rhea, 2006). As a result of obstacle contact, toe clearance and peak elevation are subsequently increased in the contacting limb (Rhea & Rietdyk, 2011) in an effort to guarantee clearance over the obstacle, thus decreasing the risk of tripping and resulting injury (Patla et al., 1996). It has been suggested that increased clearance is exhibited for at least 30 subsequent obstacle crossings (Heijnen et al., 2012).

The lower limbs have been shown to be independently controlled while crossing an obstacle (Heijnen et al., 2014; Patla et al., 1996; Rhea & Rietdyk, 2011) as the leading limb trajectory and the trailing limb trajectory differ from each other (Patla, Rietdyk, Martin, & Prentice, 1996) Compared to the lead foot, he trail foot exhibits a larger overall vertical elevation during obstacle crossing (Sparrow et al., 1996). This may be a result of available visual information as the lead limb is observable in the lower visual field during crossing due to its anterior position compared to the body, and therefore may be used to modulate the foot trajectory over the obstacle (Mohagheghi et al., 2004; Patla, 1998; Patla et al., 1996; Rietdyk & Rhea, 2006, 2011). In comparison, the trailing limb is posterior to the body and the obstacle is inferior to the body during crossing, therefore visual information is absent and unable to be utilized as a control strategy (Hill et al., 1997; Patla et al., 1996). This requires more reliance on visual exproprioceptive input and viewing the obstacle during approach (Heijnen et al., 2014). Evidence for independent control also lies within obstacle contact. The trail limb has a higher probability of contacting the obstacle than the lead limb (Heijnen et al., 2014; LoJacono et al., 2018; Mohagheghi et al., 2004; Rhea & Rietdyk, 2007, 2011, 2011; Rietdyk & Rhea, 2006).

Once obstacle contact occurs, trail foot clearance increases by 75% and lead foot clearance remains unchanged during subsequent crossings (Heijnen et al., 2012), giving further evidence for independent control of the lower limbs as control of one limb is not dependent on the movement of the other (Heijnen et al., 2012; Patla et al., 1996; Rhea & Rietdyk, 2011).

In healthy adults, there is some commonality in the way obstacles are crossed. During multiple obstacle crossings of the same height, we exhibit similar foot placement before the obstacle of the trail limb and a similar lead foot clearance (Chen, Ashton-Miller, Alexander, & Schultz, 1991). In response to crossing an obstacle, healthy adults exhibit an upward bias of the swing limb trajectory which may be thought of as a more vertical displacement of the hip in the swing limb. Additionally, the swing limb exhibits an increased hip and knee flexion (Patla et al., 1991; Patla & Rietdyk, 1993). Additionally, healthy adults are able to similarly modify foot placement and toe clearance in response to changes in obstacle height and width (Patla et al., 1991; Patla & Rietdyk, 1993; Rietdyk & Rhea, 2011).

In response to obstacle height, adaptations in lead limb trajectory begin at toe-off (Patla & Rietdyk, 1993) with adjustments in limb trajectory occurring during the swing phase (Patla et al., 1996). Increases in obstacle height result in increased trail limb clearance as well as lead foot crossing time as the lead foot begins to cross progressively earlier within the step before the obstacle (Sparrow et al., 1996). This may allow more time for the lead foot to successfully traverse the obstacle (Sparrow et al., 1996) and ensure a proper lead foot placement after the obstacle for stable weight-bearing single stance phase during trail foot crossing. Additionally, as obstacle height increases, the horizontal braking impulse just before crossing also increases in order to decrease the velocity of the body, allowing for better adjustments to be made to maintain safety and stability during crossing (Patla et al., 1991). With increasing heights, approach speed toward the obstacle is relatively sustained; however, during crossing, crossing speed significantly decreases and foot clearance significantly increases (Chen et al., 1991).

Patients with aging and various pathologies respond differently to obstacle crossing when compared with healthy adults. Older adults approach and cross obstacles at a slower rate along with exhibiting a smaller step length over the obstacle, indicating a more conservative approach to obstacle crossing compared to younger adults (Chen et al., 1991; Muir, Haddad, Heijnen, & Rietdyk, 2015). Older adults also exhibit a more vertical toe-off of the lead foot just before crossing, resulting in an overshoot of the foot in its trajectory that must then be corrected by retracting backwards before landing in its final placement that is closer to the backside of the obstacle (Muir et al., 2015). This lead overshoot progressively increases with age (Muir et al., 2015). Additionally, older adults cross the obstacle so that it is 10% further forward within their obstacle-crossing step (Chen et al., 1991). This is potentially due to an effort to allow more time to be available to respond to the obstacle and to better adapt their limb trajectory as older adults are more likely to contact an obstacle under smaller available response times than younger adults (Chen, Ashton-Miller, Alexander, & Schultz, 1994). Lastly, with aging, head angle becomes lower and more directed at the feet, potentially in an effort to obtain more visual information before crossing the obstacle (Muir et al., 2015).

Visual Information for Gait Adaptation

Visual information is vital for effective and accurate control of gait and adaptation to environmental perturbations (Patla, 1998). Vision is used to globally control the body's ambulation as well as more specific locomotive tasks. An example of visual information used for global locomotion is optic flow. Optic flow is crucial to ambulation as it is used continuously to regulate locomotion (Matthis & Fajen, 2014) via the nervous system's control of the body's velocity (Patla, 1997). Another example of visual information for global locomotion is "obstacle memory", which utilizes obstacle size and position to modify the limb trajectory over an obstacle in subsequent obstacle crossings (Heijnen et al., 2014). This may be executed by memory of a previous experience with crossing the obstacle or when viewing the obstacle during approach (Heijnen et al., 2014). Additionally, visual input provides proactive regulation of dynamic stability during locomotion and adjustments for different surfaces and uneven (Matthis & Fajen, 2014; Patla, 1997) terrain through intermittently sampling obstacles and footholds that lie ahead (Mohagheghi et al., 2004; Patla et al., 1996). Lastly, visually observed and inferred properties of the environment influence the avoidance strategy selection for obstacles (Patla, 1998). For example, perceived fragility increased toe clearance in an examination of solid versus fragile obstacles (Patla et al., 1996).

During more specific tasks, vision may control a particular aspect. This may be exemplified in an obstacle crossing task. Obstacles require adaptations of gait which may be responses that are reactive (via feedback mechanisms) or proactive (via feedforward mechanisms) in their execution of movement pattern changes. Feedback mechanisms are responses to sensory stimuli after a perturbation occurs, most commonly in the form of proprioceptive or visual information, such as slipping on ice or seeing an object move into the gait path. Feedforward mechanisms utilize visual information and previous experiences to plan for a movement execution to a perturbation already within the environment, such as a static obstacle or recalled experience of an uneven terrain. During obstacle crossing, vision modulates and modifies limb trajectories in both a feedforward manner to plan for obstacle avoidance and a feedback manner to make online changes in trajectory during crossing (Patla, 1998; Patla & Greig, 2006; Rietdyk & Rhea, 2011).

Visual exteroceptive information about obstacles has been shown to be utilized as a feedforward mechanism to regulate swing limb trajectory (Patla, 1998; Patla et al., 1996) and foot placement (Patla, 1998), as well as plan an obstacle avoidance strategy (Patla, 1997; Patla et al., 1991). In order to plan an obstacle avoidance strategy, the obstacle must be visible in the approach before crossing to gather visual information and form a memory of the obstacle's characteristics to guide the trajectories of the limbs during crossing (Heijnen et al., 2014). The obstacle must be in view during the approach until at least two steps before crossing (Matthis & Fajen, 2014; Mohagheghi et al., 2004; Patla et al., 1991) and the top and lower edge of the obstacle must be visually unobstructed (Heijnen et al., 2014; Rhea & Rietdyk, 2011) to successfully avoid the obstacle. Withdrawing the ability to view the obstacle five steps before crossing has been shown to result in incorrect foot placement and reduce the rate of successfully crossing the obstacle to 50% (Patla & Greig, 2006). On the other hand, feedback mechanisms are crucial for online changes in limb trajectory and usually result in online modifications within a single step. Visual input about limb position and movement is used to fine tune obstacle crossing trajectory within a single step (Patla, 1998; Patla et al., 1996).

Fall-Risk Factors Related to Gait and Balance in Older Adults

Issues with gait may be a result of simple age-related changes in gait and balance, as well as from specific dysfunctions of the nervous, muscular, skeletal, circulatory, and respiratory systems or from physical deconditioning due to physical inactivity (Rubenstein, 2006). Major risk factors for falling are the adoption of inappropriate neuromuscular control strategies with respect to poorer adaptive walking responses (Berg et al., 1997) and poorer postural control and balance (Maki et al., 1994). Older adults have a decreased ability to control their balance and walking (Maki et al., 1994; Rubenstein, 2006; Tinetti et al., 1988; Vellas et al., 1997) due to age-related changes in reaction time (Lajoie & Gallagher, 2004), muscle mass/strength (Goodpaster et al., 2006), and attention/cognitive ability (Mirelman et al., 2012). Impaired sensory, integrative, and/or motor functioning will negatively affect gait and balance and increase fall risk. Some examples include: decreased proprioception in the lower limbs as a result of neuropathy, visual impairment and decreased visual contrast sensitivity, increased body sway, and decreased ankle dorsiflexion strength (King & Tinetti, 1995).

Poor adaptive gait responses exhibit increased stride variability (Maki, 2015) and loss of stride interval complexity (Lipsitz, 2002, 2004) resulting in a loss of functional capacity, thus increasing fall risk (Hausdorff, 2007). Decreased gait speed, step length, and step width are also indicative of an increased fall risk in older adults (Chen et al., 1994; Chen et al., 1991; Muir et al., 2015). Poor adaptations to obstacle perturbations that may lead to a trip or fall are characterized by a decreased ability to adapt foot trajectory within the obstacle crossing step (Berg et al., 1997), as well as maintaining a foot trajectory that is closer to the obstacle during initiation and termination of crossing and while crossing the obstacle (Chen et al., 1994; Chen et al., 1991; Muir et al., 2015). These poor adaptive walking responses increase the risk of obstacle contact and the potential for a trip and/or fall.

Decrements in postural control are also indicative of increased fall risk (Maki et al., 1994). Postural control is defined as the ability to maintain equilibrium in a gravitational field by keeping or returning the center of mass over its base of support (Horak, 1987). Postural control reflects balance ability and is crucial to maintaining a mobile and independent quality of life as it allows for completion of global tasks, such as walking and standing, as well as more specific tasks, such a reaching or transferring (Haddad, Rietdyk, Claxton, & Huber, 2013; Maki et al., 1994). Postural control may be measured by tracking the center of pressure (CoP) – the vertical ground reaction force underneath the feet – in both the anteroposterior and mediolateral directions. The CoP may be tracked in terms of displacement amplitude and velocity. Larger amplitudes of CoP displacement in the mediolateral direction (Maki et al., 1994; Swanenburg et al., 2010) and increased velocity in the anteroposterior direction (Berg et al., 1992) indicate higher risk of falling. In order to examine the aforementioned fall-risk factors related to gait and balance, a variety of measurements and tools have been developed to assess gait and balance ability.

Measurements of Gait and Balance

Commonly utilized measurements of gait and balance in clinical settings utilize a wide variety of tests including the Functional Gait Assessment (FGA), Timed Up and Go (TUG), and Berg Balance Scale (BBS). The FGA was created from the Dynamic Gait Index (DGI), which assessed postural stability in during gait in older adults (age>60 years) at risk of falling. The DGI showed a ceiling effect in individuals with vestibular disorders as some of the questions did not sufficiently challenge postural stability. Thus, the FGA scale was created to add tasks to challenge patients with vestibular disorders. The FGA is a 10-item clinical gait test that asks participants to perform the following gait activities: walk at normal speeds, at fast and slow speeds, with vertical and horizontal head turns, with eyes closed, over obstacles, in tandem, backward, and while ascending and descending stairs (Wrisley et al., 2004). The FGA with a cutoff score of 22/30 is effective in classifying fall risk in older adults and predicting unexplained falls in community-dwelling older adults (Wrisley & Kumar, 2010).

The TUG is a test of basic functional mobility. For this test, participants are seated in a chair and then asked to complete the following (as quickly and as safely as possible): rise from the chair, walk to a line on the floor 3 meters ahead, turn around, return to the chair, and sit back down. Time taken to complete the test is measured (Podsiadlo & Richardson, 1991). Community-dwelling older adults who take longer than 14 seconds to complete the test are at a higher risk of falling (Shumway-Cook et al., 2000).

The BBS is a test of functional balance in everyday living. Participants perform a series of balance tasks which increase in difficulty from quiet stance, sit-to-stand, weight shifting, reaching, turning in place, single leg stance, tandem stance, to foot raising. Each task is timed and/or rated with a score from 0 to 4, with the highest possible score being 56 (Berg, 1989). A cutoff score of 45 and lower indicates a difference between individuals who are safe in independent ambulation and individuals who require assistive devices or supervision when walking (Berg, Wood-Dauphinee, Williams, & Maki, 1992) and classifies these older adults as fallers (Lajoie & Gallagher, 2004).

With the advancement of technology, portable tools have been created to objectively assess gait and balance metrics, including the BTrackS balance plate and the AccWalker smartphone application. The BTrackS balance plate was developed as completely portable, inexpensive force plate for balance testing in a wide spread of clinical settings (Goble, Hearn, & Baweja, 2017; Goble, Manyak, Abdenour, Rauh, & Baweja, 2016) and has shown to be reliable and valid in older adults (D. Goble et al., 2017; D. J. Goble & Baweja, 2018; Levy et al., 2018). BTrackS tracks the center of pressure (CoP) during quiet standing to determine a balance score (O'Connor et al., 2016). Additional obtainable metrics are CoP path length, mean velocity, and variability. The protocol consists of 3 static stance trials with participants standing as still as possible for 20 seconds with eyes closed, feet shoulder-width apart, and hands on hips. Poor postural control is defined as a higher balance score, greater CoP movement (increased path length), and greater CoP rate of movement (increased mean velocity).

Smartphones are readily available devices which can be used via smartphone applications to measure gait and balance. Smartphone apps can tap into the phone's sensors and detect spatial and temporal aspects of motion in all three planes (Roeing et al., 2017). Kinematic data can be extracted to determine range of motion, velocity, acceleration, as well as complex variability metrics, such as detrended fluctuation analysis, coefficient of variation, and sample entropy. These kinematic data can be used to assess gait function, balance, and fall risk. Smartphone apps to assess gait and balance typically utilize static positions to assess neuromotor control. While valuable, static balance does not fully capture the ability of an individual to respond to perturbations during gait and balance-challenging activities. A smartphone application that assesses neuromotor control during a dynamic task may be more representative of overall gait and balance ability. In addition, a majority of smartphone applications designed to monitor balance and fall risk were not evaluated on their validity and reliability. Only 38% evaluated validity and 23% evaluated reliability (Roeing et al., 2017); therefore, the extent to which smartphone apps may be acceptably used in research is minimal at this time.

The AccWalker app is a reliable and valid Android phone application that tracks spatial, kinematic, and temporal characteristics of the thigh to characterize temporal and kinematic variability as a measure of neuromotor control during a dynamic task (Kuznetsov et al., 2018). The phone is placed in a strap around the middle outer portion of the thigh. Participants are instructed to step in place for 70 seconds for 3 trials of each of 3 separate conditions: eyes open, eyes closed, and headshake. AccWalker has been used in healthy adults and populations with neurological insult, including sub-concussed (Bailie et al., 2018; Rhea, Kuznetsov, Robins, Jakiela, Long, et al., 2017; Rhea, Kuznetsov, Ross, et al., 2017; Rhea et al., 2018; Schneider et al., 2017) and concussed individuals (Kuznetsov et al., 2017; Rhea, Kuznetsov, Robins, Jakiela, LoJacono, et al., 2017). In active duty U.S. navy personnel who completed training involving repetitive low-level blast exposure (sub-concussive events), AccWalker determined slower movement pace and increased stride time variability after training (Rhea, Kuznetsov, Ross, et al., 2017). AccWalker has also been used to track decrements in dynamic balance within concussed individuals after 10 days and up to 6 months after a concussion (Rhea, Kuznetsov, Robins, Jakiela, LoJacono, et al., 2017).

Patient-Reported Outcomes

Fall risk in older adults is not only tied to a decrement in gait and balance control, but also to how individuals perceive their health and well-being. Patient reports are indicative of their thoughts towards their own capabilities and perceptions, and have been validated as an indicator of actual fall risk (Cumming et al., 2000; Lajoie & Gallagher, 2004). The Medical Outcomes Study 36-item Short Form health survey (SF-36) measures physical and mental health-related quality of life (Ware Jr & Sherbourne, 1992). Represented within the SF-36 are 8 health scales: physical functioning, social functioning, role functioning (physical and emotional), mental health, vitality, pain, general health perception, and health change. Items from these 8 scales represent 3 main aspects of health: functional status, well-being, and overall evaluation of health

(McHorney et al., 1993). Higher scores on the SF-36 indicate more favorable health states (Brazier et al., 1992) as low scores on the SF-36 are associated with low fall-related self-efficacy, increased fear of falling, and reduced ability to perform activities of daily living (Cumming et al., 2000), thus increasing the risk of falling.

Fear of falling has been directly linked to poorer postural control performance in those who have fallen and those who have yet to fall (Maki et al., 1991). If an individual is more afraid of falling and subsequent injury, they will likely limit their physical activity which will lead to deterioration in physical capabilities and neuromuscular control strategies, which will further increase risk of falling (King & Tinetti, 1995). The Activities of Balance Confidence (ABC) scale addresses the extent to which an individual is afraid of falling within a balance continuum by providing a measurement of confidence in completing balance-challenging activities of daily living. The ABC is a 16-item self-efficacy scale that is scored on a 10-point ordinal scale (Myers et al., 1996; Powell & Myers, 1995). Participants rate their confidence in maintaining their balance while performing 16 activities of daily living. The ABC has been shown to correlate with physical function level in older adults (Myers et al., 1998). A score less than 50 indicates a low level of functioning typically seen in adults receiving home care. A score between 50 and 80 indicates a moderate level of functioning seen in older adults with chronic health problems or living in retirement centers. Finally, a score greater than 80 indicate high functioning seen in physically active older adults (Myers et al., 1998). In terms of fall risk, an ABC score of less than 67 indicates an increased risk of falling (Lajoie & Gallagher, 2004). In sum, a lower score on the ABC represents a decreased balance confidence and is associated with decreasing physical functioning (Myers et al., 1998), balance-impairment (Cho, Scarpace, & Alexander, 2004), and falls (Lajoie & Gallagher, 2004) and is the most predictive of falling in older adults (Landers et al., 2016).

This and the previous section outlined common ways that gait and balance capacity can be measured using patient reported outcomes and motor ability tests. While these assessments are useful in providing a snapshot related to fall-risk factors, it remains unclear how to best modify characteristics associated with these assessments to ultimately decrease fall risk. Previous fall prevention programs have shown some benefits and efficacy (Chase et al., 2012; Guirguis-Blake et al., 2018),; however, there are a variety of barriers to the success of these programs due to financial, resource, and social constraints (Child et al., 2012; McMahon et al., 2018; Shier et al., 2016). New technology, such as virtual reality (VR) may provide unique opportunities to provide motivational training in novel and individualized ways, which could lead to greater efficacy in fall prevention.

Virtual Reality

Fall prevention interventions have utilized a variety of methods including education, medication changes, psychological interventions, exercise, and multifactorial approaches (Chase et al., 2012; Guirguis-Blake et al., 2018; King & Tinetti, 1995; Lipsitz, 2002). Despite the design of a variety of fall-risk prevention programs, many have limitations that prevent successful implementation, including financial, resource, and social barriers (Child et al., 2012; McMahon et al., 2018; Shier et al., 2016). As a result, falls continue to pose significant risks for older adults in terms of injury and morbidity. Virtual reality may be a solution to these barriers as it is cost-effective, resource-efficient, and can be a highly engaging environment.

Virtual reality (VR) has become a very plausible means of rehabilitation and is becoming more commonly used in conjunction with traditional rehabilitation techniques as clinicians seek to improve rehabilitation methods with more advanced techniques and technology. A variety of populations have benefitted from training with VR components, such as patients with Parkinson's, multiple sclerosis, acute and chronic post-stroke hemiplegia, traumatic brain injury, and cerebral palsy (Cano Porras et al., 2018). VR has shown improvements in balance, gait spatiotemporal measures, and kinematics – such as walking speed, stride length, walking endurance, balance control, mobility, and obstacle crossing (Baram & Miller, 2006; Cano Porras et al., 2018; K. Cho et al., 2012; Darter & Wilken, 2011; Gates, Darter, et al., 2012; Jaffe et al., 2004; A. Lee et al., 2014; Liao et al., 2015; LoJacono et al., 2018; Mirelman et al., 2011, 2016b; Shema et al., 2014a; Sin & Lee, 2013). Training in VR has also shown improvements in clinical tests, such as the TUG, BBS, FGA, Four Square Step Test, and the 10-minute walk test (Cano Porras et al., 2018).

The use of VR is defined as a simulation of the real world environment that is generated through computer software and is experienced by the user through a human-machine interface (Holden, 2005). VR began in 1962 with Morton Helig's Sensorama – a personalized video arcade of sorts that contained 3D video feedback, motion, color, stereo sound, aromas, wind effects, and a vibrating seat. Helig began working on a head mounted display (HMD) which was continued by Ivan Sutherland, who realized that he could utilize computer-generated scenes instead of analog images. The military and NASA became very interested in the idea of computer-generated virtual environments to create digital flight simulators to replace their costly analog simulators. In the 1980s, NASA created the first HMD to utilize an LCD display, similar to the LCD technology that today's commercially available HMDs utilize. However, this developed technology required high end processors housed in computers that, at the time, were very bulky and expensive. Thus, scientific researchers turned to more affordable options, initially using desktop computers and computer joysticks for non-immersive interaction with a virtual scene.

Within the 21st century, technology has rapidly progressed to provide enhanced graphics cards and stronger processors to better develop virtual scenes and advance user interfaces. A variety of interfaces have been utilized with VR, which vary relative to the degree of immersiveness of the user. Immersiveness can be thought of as a continuum, with desktop screens on one side and augmented reality headsets on the other. The more immersive an interface is, the more direct the user interactions with virtual objects become. More immersiveness provides the user with a better perception that the virtual environment is real and three-dimensional, which is referred to as presence. Presence declines as virtual environments become less immersive (Holden, 2005).

However, non-immersive interventions may still be effective even though they elicit less presence. Previous research has shown that training programs utilizing treadmills and flat screens depicting a VR environment with real-time feedback of foot position have been successful in changing metrics of gait and balance in a variety of populations. Individuals with mild cognitive impairment (Mirelman et al., 2016b) and Parkinson's (Mirelman et al., 2011), as well as younger (LoJacono et al., 2018) and older adults (LoJacono et al., 2018; Mirelman et al., 2016b; Shema et al., 2014a) have benefitted from this specific VR interface. Participants saw improvements in gait speed, walking endurance, balance control, obstacle crossing ability, and a decrease in fall rate (LoJacono et al., 2018; Mirelman et al., 2011, 2016; Shema et al., 2014). Additionally, surround screens, such as the CAREN system, have been utilized to create visually and physically destabilizing environments to understand how dynamic margins of stability may change under different perturbation conditions in healthy adults (Young et al., 2012) and individuals with lower-limb amputations (Beltran et al., 2014). This system has also been used to test the feasibility of VR gait rehabilitation with patients post-stroke (Fung et al., 2006) and with multiple sclerosis (Kalron et al., 2016). However, non-immersive VR systems rely on treadmills or platforms, limiting the natural degrees of freedom for an individual to train in. Thus, immersive HMDs have been created to allow for training overground in all 3 planes of motion, most similarly to our natural everyday interactions with the real-world.

Original HMDs utilized in research were generally very bulky, heavy, and expensive. They required a powerful processing desktop computer, limiting the motion capabilities of the participant, and were reliant on integration with motion capture for detection of head tilt and real-time feedback. Recently, commercial companies have begun to enter the VR HMD space, allowing for many users to purchase off-the-shelf VR

HMD technology to interact with video games in a completely immersive manner, such as Sony's PlayStation VR, Facebook's Oculus, and HTC's Vive series. These new off-the-shelf VR HMDs are relatively inexpensive, much lighter, are usable with portable laptop computers, come with small portable motion capture cameras for positional tracking, and are more recently becoming wireless. This new class of advanced HMDs allow for their use anywhere and anytime, making them of increased interest to researchers and clinicians alike. Additionally, free VR environment-rendering software platforms, such as Unity, allows for an endless possibility of virtual environments that can be tailored to a specific population and creation of customized difficulty levels that can be tailored to a specific individual. Thus, researchers and clinicians have become even more interested in the employment of this technology.

However, interest in using virtual reality in a clinical setting to prevent falls or enhance gait and balance must be cautionary. Training utilizing VR must be heavily considered within the context of motor learning before it can be applied in a clinical setting. Motor learning is crucial for the acquisition, transfer, and retention of motor skills; thus, the field of motor learning and the applications of its principles must be thoroughly considered before designing and implementing a training program utilizing VR. Much is still unknown about how motor learning principles are applied in virtual reality and if they are the same in VR as they are in the real-world.

Motor Learning

The field of motor learning is crucial to understanding how to optimize efficiency and efficacy of fall prevention programs. Repetition is key to learning and improving motor skills and is an important aspect of training within fall prevention programs. Practice is essential for motor learning, but it depends on how it is scheduled, distributed, and varied. With reference to scheduled practice, a blocked schedule of a set of tasks (practicing a single task at a time) is better for skill acquisition, however a random schedule of the same tasks enhances retention during both random and blocked retention tests (Shea & Morgan, 1979). These results are due to the theory of contextual interference. The Contextual Interference theory suggests that higher levels of contextual interference lead to poorer performance than lower levels during acquisition, yet provide superior retention and transfer effects (Battig, 1972). Thus, random practice (high contextual interference) outperforms blocked practice (low contextual interference) on retention tests (Shea & Morgan, 1979). Additionally, the specificity of practice hypothesis suggests random scheduling of practice is better for learning and retention because the environment and movement context during the random practice environment and the random retention environment are the same, thus optimal performance is achieved (Proteau et al., 1992).

Practice must also be appropriately distributed to enhance motor learning and training. Longer rest intervals in between task repetitions (distributed practice) improves retention compared to having very little rest between practice periods (massed practice) (Lee & Genovese, 1988). It is plausible that massed practice may result in larger amounts of fatigue which may degrade performance and interfere with learning; whereas distributed practice may enhance retention as it allows for fatigue to dissipate. However, it is important to understand the nature of task, whether it is continuous or discrete, as this relationship changes as a result of the nature of the task. In continuous tasks, distributed practice is better in terms of acquisition performance and retention; On the other hand, massed practice is better for acquisition performance and retention for discrete tasks (Lee & Genovese, 1989). This may be because continuous tasks require more time to make decisions and evaluate between trials due to the increased length of time it takes to complete the tasks and the increased amount of information that needs to be processed. Whereas discrete tasks are short in duration and require relatively simple decisions and evaluations in between trials (Lee & Genovese, 1989).

Variability of practice is also crucial to consider when creating a training program to enhance learning. Constant practice involves only a single member of a class of tasks (i.e. a set distance), while variable practice involves several members of the class of tasks (i.e. different distances). During skill acquisition, constant practice outperforms variable practice, yet in transfers tasks, variable practice does as well or even outperforms constant practice (McCracken & Stelmach, 1977). The schema theory may explain these results. The schema theory refers to a set of rules (schemas) that a learner acquires and relates to a specific action (Schmidt, 1975). With practice, the schema is continually developed to create the parameters of a generalized motor program. Thus, variable practice enhances the development of schemas for more effective novel task performance, and therefore, generalizability of the motor schema (Catalano & Kleiner, 1984).

Feedback is crucial for motor learning as it provides both intrinsic and extrinsic sources of information about performance. Intrinsic feedback is natural information that comes from inherently completing a movement. Extrinsic feedback (augmented feedback) is also known as performance-related information in addition to task-intrinsic feedback that influences how the participant directs their attention (Schmidt & Lee, 2014). Augmented feedback may be divided into two categories: knowledge of results (KR) and knowledge of performance (KP). KR is externally-presented information about success of an action relative to the goal of the performance (i.e. pass/fail, score). In contrast, KP gives information about the movement pattern that led to the performance outcome (i.e. limb position, angle relative to the body) (Schmidt & Lee, 2014). Augmented feedback allows the performer to understand information about their success and allows for the determination potential strategies to enhance their performance, thus learning the skill. It is important to note that the learning principle of feedback is very complex and integrative as learning may be both positively and negatively influenced by augmented feedback in a variety of ways, such as whether or not it is given, type of feedback given (KP vs. KR), how it is given (frequent or summary), and when it is given (early or later in learning). The correct way to deliver feedback may depend on the skill of the learner and the stage of learning the performer is in.

There are many theories for why augmented feedback promotes learning. The first relates to motivation. The self-determination theory (SDT) provides an overall understanding of the types of motivation and their influence on an individual (Deci & Ryan, 2008). SDT categorizes motivation into autonomous and controlled motivation. Autonomous motivation consists of intrinsic motivation and aspects of extrinsic motivation that someone identifies with an activity's value and integrates with their sense of self, whereas controlled motivation consists of external regulation (via reward or punishment) and introjected regulation (via others' approval, advance of shame, self-esteem). Both types of motivation influence one's behavior compared to amotivation (lack of motivation), however autonomous motivation tends to show better performance and retention of behaviors (Deci & Ryan, 2008)

Feedback is indirectly motivating as it provides information to performers to keep them actively engaged in the task and practicing, thus benefiting learning. However, feedback is directly motivating when given positive feedback. It has been shown that giving positive feedback after well-performed trials is more beneficial for learning compared to giving negative feedback after poorly performed trials as demonstrated by enhanced retention of performance (Chiviacowsky & Wulf, 2007). It is possible that positive feedback is a form of autonomous motivation as they are comparing their performance with their intrinsic capabilities and are integrating the good performance with their sense of self. Receiving positive normative feedback, which informs an individual they are performing better than the average of their peers, enhances learning and retention compared to receiving negative normative feedback about performing worse than the average of their peers (Lewthwaite & Wulf, 2010). Additionally, receiving no feedback results in even worse performance than receiving either the positive or negative normative feedback (Lewthwaite & Wulf, 2010). It is possible that this normative feedback fuels controlled motivation due to the social comparison of their peers, and provides evidence for amotivation when receiving no feedback during a task.

Another theory related to augmented feedback and learning is the attentional focus theory. KR provides information about the success of the performance relative to the goal and thus directs the learner's attention outward towards the goal of the movement (external focus of attention). KP provides information about the actual movement and how it was produced, thus directing the learner's attention inwardly toward the movement itself (internal focus of attention). An external focus of attention has been shown to more effectively enhance performance than an internal focus of attention, a result that has repeatedly been found in a variety of motor learning and performance contexts (Wulf, 2013). This result may be explained via the constrained action hypothesis. In this hypothesis, an external focus of attention enhances performance because it allows our natural, unconsciously-controlled automated processes to control our movements to accomplish the movement goal. On the other hand, an internal focus of attention negatively affects performance because it induces a conscious control which interferes with the automated processes and constrains the motor system (Wulf et al., 2001). Thus, the idea that KR is inherently externally focused may affect how feedback promotes motor learning.

Motor Learning in Virtual Reality

Virtual reality offers an advantage for learning motor skills because it is well suited to provide participants with all three of the aforementioned motor learning concepts of practice, feedback, and motivation. All of these are important to consider when integrating VR into clinical settings as a prevention/rehabilitation tool. VR is highly programmable, making motor learning principles easy to apply and manipulate within the virtual environment in a variety of ways. For example, repetition of the different movements can be programmed into the environment or cued within the environment to allow for repetitive, varied practice in a safe manner. Within a virtual environment, repetition must be linked to incremental success at a task or goal (Holden, 2005). Augmented feedback can be programmed into the environment in any form (both KP and KR) with specified timing and frequencies. This may be achieved through feedback about performance success in terms of KR and/or about movement validity/real-time feedback of limb position in terms of KP.

An individual must be motivated for repeated practice in order to see incremental performance successes (Holden, 2005). Virtual reality experiences can be highly engaging both physically (because it requires the user to interact with obstacles in their virtual environment) and mentally (because it feels like a game as the use is submersed within a different world). People typically find VR inherently fun due to its potential to provide game-like interactions and are therefore more motivated and cognitively engaged in the task at hand (Cano Porras et al., 2018; Howard, 2017). This high engagement provides crucial motivation for rehabilitative applications that require consistent, repetitive practice that may otherwise not be engaging within a medical office or rehabilitation clinic.

It is possible that training in VR may promote motor learning to a greater extent than real-world training (Holden, 2005; Howard, 2017). Studies have shown that adding VR to training enhanced learning above and beyond traditional training mechanisms (Jaffe et al., 2004; Mirelman et al., 2011, 2016b). It has been suggested that VR learning scenarios may influence motor learning above and beyond the real-world learning scenarios due to what VR can provide that would be unavailable in the real world. For example, VR has the potential to completely reduce and diminish any external distractions that would otherwise be apparent in real world training and allow users to intently focus on the specific task at hand. Additionally, VR can provide external real-time feedback which would otherwise not be available in the real-world. For example, objects or virtual representations of the body could change color to give information about success (KR), or different auditory cues could play in response to success/failure in achieving a goal or specific movement in order to manipulate KR or KP.

The potential issue, which must be recognized and confounds the idea that VR is as effective or better at producing motor learning, is that not all VR systems or environments are spatially accurate and map onto real world perceptions of body position in a 1:1 ratio (Keshner & Fung, 2017). We must be cognizant of the fact that training based on motor learning rely on accurate perception and spatial mapping. For example, Fitt's Law and the speed-accuracy trade-off suggest that learning is a function of improved accuracy and speed within accomplishing a task (Fitts, 1954). If the spatial mapping is incorrect and perception is off, then accuracy could decline and this function could be negatively affected. However, there is an argument that even though the spatial mapping is not 100% accurate, it enhances task difficulty. Thus, keeping participants motivated and cognitively engaged in the task at hand (Keshner & Fung, 2017).

Previous Research

Our previous research has examined changes in performance during VR obstacle crossing and resulting changes in real-world obstacle crossing strategies in order to understand the application of motor learning principles (skill acquisition, transfer, and retention) within VR. We utilized a virtual obstacle crossing environment depicted on a projection screen in front of a treadmill (LoJacono et al., 2018). In our first study, young healthy adults (*N*=20, 22.4±3.7yrs) and middle-aged healthy adults (*N*=20, 55.6±5.99yrs) participated in two sessions of VR obstacle crossing (VR training) preceded and followed by a set of real-world obstacle crossings (pre-/post-testing). During VR training, virtual feet moved in real-time with the participant's own feet and subjects were instructed to step over the red virtual obstacle. Virtual obstacle crossing practice resulted in significant improvements in foot elevation and success rate for both groups during the subsequent virtual obstacle crossing session (10% increase for younger adults and 9% increase for older adults), indicating the learning of a new skill. These improvements in performance are indicative of skill acquisition and motor learning (LoJacono et al., 2018). Additionally, this performance improvement in the virtual environment transferred to the real-world via a safer obstacle crossing strategy evidenced by increased foot clearance over physical obstacles and an earlier initiation of crossing for both groups (LoJacono et al., 2018).

In a follow-up study, we replicated the study with set of young healthy adults (*N*=20) and added a retention component of real-world obstacle crossing 48 hours later to establish that motor learning in fact occurred. The results again showed that foot clearance significantly improved from pre- to post-training ($p<0.05$), and lead foot clearance over the obstacle was significantly retained 48 hours later ($p<0.05$), while trail limb clearance remained elevated albeit not significant (LoJacono et al., 2017). This study showed that VR training is capable of producing more permanent changes in the real-world.

Collectively, these studies showed that one day of training within the VR environment resulted in improvements in skill acquisition, transfer, and retention albeit the total training duration being relatively short (25 single obstacle crossings; ~12.5 minutes of training). It remains unknown what performance changes will be exhibited over multiple days/weeks of training. It is plausible that performance will continue to increase as practice time increases and more feedback is given for a longer duration of time. It is important to determine the optimal training duration (i.e., when learning has occurred, if there is a learning curve, and if performance plateaus) to further enhance motor learning and create more permanent real-world changes.

Current Gaps in the Literature with Regards to This Dissertation

Previous VR studies typically focused on older adults who already had cognitive and physical impairments and disorders, such as Alzheimer's, Parkinson's, mild cognitive impairments, post-stroke, and idiopathic falling (Mirelman et al., 2011, 2016; Shema et al., 2014). These previous studies did not include a healthy older adult group as a control. This limits current VR training findings to older adults as a rehabilitation tool for disease, disorders, and falling, and does not indicate the potential for VR to be used a preventative tool for those who are physically and cognitively healthy. It is important to establish normative data of older adults' behavior within a virtual environment to understand the point at which an individual can successfully use VR to improve known risk factors for falling, and to understand the feasibility of using VR as a fall prevention tool.

Another limitation of previous studies is that they have been limited to non-immersive VR environments constrained to treadmills (LoJacono et al., 2018; LoJacono, et al., 2017; Mirelman et al., 2011, 2016b; Shema et al., 2014)**.** Treadmills constrain participants to only anteroposterior and longitudinal directional movement and limit any potential for mediolateral avoidance strategies. Common strategies for obstacle avoidance within VR treadmill training restricts users to modify only stride length and/or step height to be successful within training (Shema et al., 2014). The way we naturally interact with our environment to avoid obstacles and maintain balance requires movement in all three dimensions with the ability to vary our speed. During VR treadmill training, the treadmill is at a constant speed which restricts the ability to modify strategies of foot trajectory.

Participants must execute final decisions more quickly, without as much time to modify foot trajectories within a single step, thus making the success rate of obstacle avoidance within VR environments lower (LoJacono et al., 2018). These treadmill limitations will be overcome in the current proposal by using head-mounted displays that allow for movement within a physical space while immersed in a virtual environment. Using an immersive HMD that allows for an overground virtual environment proposed could lead to more desirable motor learning outcomes that may better transfer to real-world obstacle crossing and other gait and balance risk factors for falling because of its overground utilization for natural obstacle crossing practice. We argue that an overground environment may be advantageous as it allows for freedom to explore overground as you would within a natural real-world environment – in all three dimensions, with varying speed, and time to adapt foot trajectories. However, it is unknown how younger and older adult will respond to and perform within an overground virtual obstacle course.

Additionally, it is unknown the extent to which a longer duration of training with an overground virtual obstacle course may improve both performance within the VR environment—in terms of number of obstacles hit and time to complete the course—and performance on real-world gait and balance measures—in terms of static balance, neuromotor control, and stationary obstacle crossings. It is important to understand how performance changes over multiple training sessions to determine the extent to which gait and balance is able to be improved and if a potential ceiling effect occurs within the virtual obstacle course.

Lastly, it is unknown how clinical outcome measures may be utilized to predict performance in VR. Clinical assessments, such as the TUG, BBS, FGA, and ABC are indicative of older adults' ability to safely navigate within our everyday environment and their ability to maintain stability and upright posture. Our unique VR environment dynamically challenges participants to both avoid and target specific obstacles in a variety of directions to sufficiently challenge the balance and adaptive walking strategies needed to succeed in safe navigation of our everyday environment, thus requiring a specific amount of confidence and general ability to adapt gait and maintain balance. It is unknown if these clinical measures may be a prerequisite measure to determine performance within a unique, dynamic virtual obstacle course environment.

CHAPTER III

OUTLINE OF PROCEDURES

Participants

We recruited 60 participants (60 intended – 35 collected; see accommodations due to COVID-19 p.61): 30 young healthy adults (aged 18-35 years; 26 collected) and 30 community-dwelling older adults (ages ≥ 60; 9 collected) from the local community. All potential participants were screened for eligibility and were excluded due to any of the following criteria: (1) Inability to walk independently for at least 15 consecutive minutes; (2) Any current musculoskeletal injuries or impairments that led to pain or discomfort during standing or walking; (3) Any diagnosed cognitive, muscular, or neurological disorders; (4) Vision that was not normal or corrected-to-normal; and (5) A Body Mass Index ≥ 30 to exclude individuals who were obese, which may differentially affect balance. The younger and older adults were quasi-randomized into either the training group (*N* = 30; 15 younger and 15 older adults) or the control group (*N* = 30; 15 younger and 15 older adults). The younger and older adult training group received training within the VR obstacle course environment and completed gait and balance testing pre-training and post-training; while the younger and older control group participated in physical activity (walking) for the same duration as the training group had in the VR environment (~15 minutes) and completed gait and balance testing pre-training and post-training.

Additionally, the younger adult training group participated in an extended training duration of 8 more sessions over 3 weeks followed by a second gait and balance post-test.

Experimental Design/Procedure

The experimental design is shown in Figure 1. All data collection was completed in the Balance and Training Laboratory at the University of North Carolina at Greensboro's main campus. The procedures for this study were approved by the local institutional review board prior to collection. Prior to arriving at the lab, participants were asked to complete an online survey (via Qualtrics) that contained an informed consent, demographics questionnaire, survey on video game/VR experience, and a set of patient-reported outcome surveys. The demographics questionnaire included basic health history, previous injuries, any surgeries to the trunk or lower-extremities, and current physical activities. The set of patient-reported outcome surveys consisted of the SF-36 and the ABC. Participants came to the lab at UNCG where they began by completing the real-world gait and balance testing for pre-training baseline measures that included a set of clinically-used motor ability tests (the FGA, BBS Question 14, simple reaction time [SRT]) as well as laboratory-developed tests (AccWalker, BTrackS balance test, and 10 real-world obstacle crossings). Participants were then placed into either a control group or a training group.

Control Groups

The older adult and younger adult control groups were asked to rest for 5 minutes after pre-training baseline measures and before completing a bout of physical activity.

They were asked to walk around the inside of Coleman gym for 15 minutes. The bout of physical activity was followed by completing the NASA-TLX and a rest period of 5 minutes. They then completed a post-test of SRT, AccWalker, BTrackS balance test, and 10 real-world obstacle crossings.

Older Adult Training Group

The older adult training group was asked to rest for 5 minutes after pre-training baseline measures and before participating in the VR obstacle course training. They completed 15 trials of the VR obstacle course before completing the NASA-TLX and resting for 5 minutes. They then completed a post-test of SRT, AccWalker, BTrackS balance test, and 10 real-world obstacle crossings.

Younger Adult Training Group

The younger adult training group was asked to complete 3 weeks of VR obstacle course training at a rate of 3 nonconsecutive sessions per week. On day 1, participants were asked to rest for 5 minutes after pre-training baseline measures and before participating in the VR obstacle course training. They completed 15 trials of the VR obstacle course before completing the NASA-TLX and resting for 5 minutes. They then completed a post-test of SRT, AccWalker, BTrackS balance test, and 10 real-world obstacle crossings. On days 2-8, they completed a session of 15 trials of VR obstacle course each day followed by the NASA-TLX. On day 9, they completed a session of 15 trials of the VR obstacle course, completed the NASA-TLX, rested for 5 minutes and then completed a second post-test of SRT, AccWalker, BTrackS balance test, and 10 real-world obstacle crossings (Figure 1). In total, the younger adult training group completed 135 trials within the VR obstacle course. In the event that a participant missed their session, they were rescheduled to participate as soon as possible. If they missed 3 sessions they were dropped from the study.

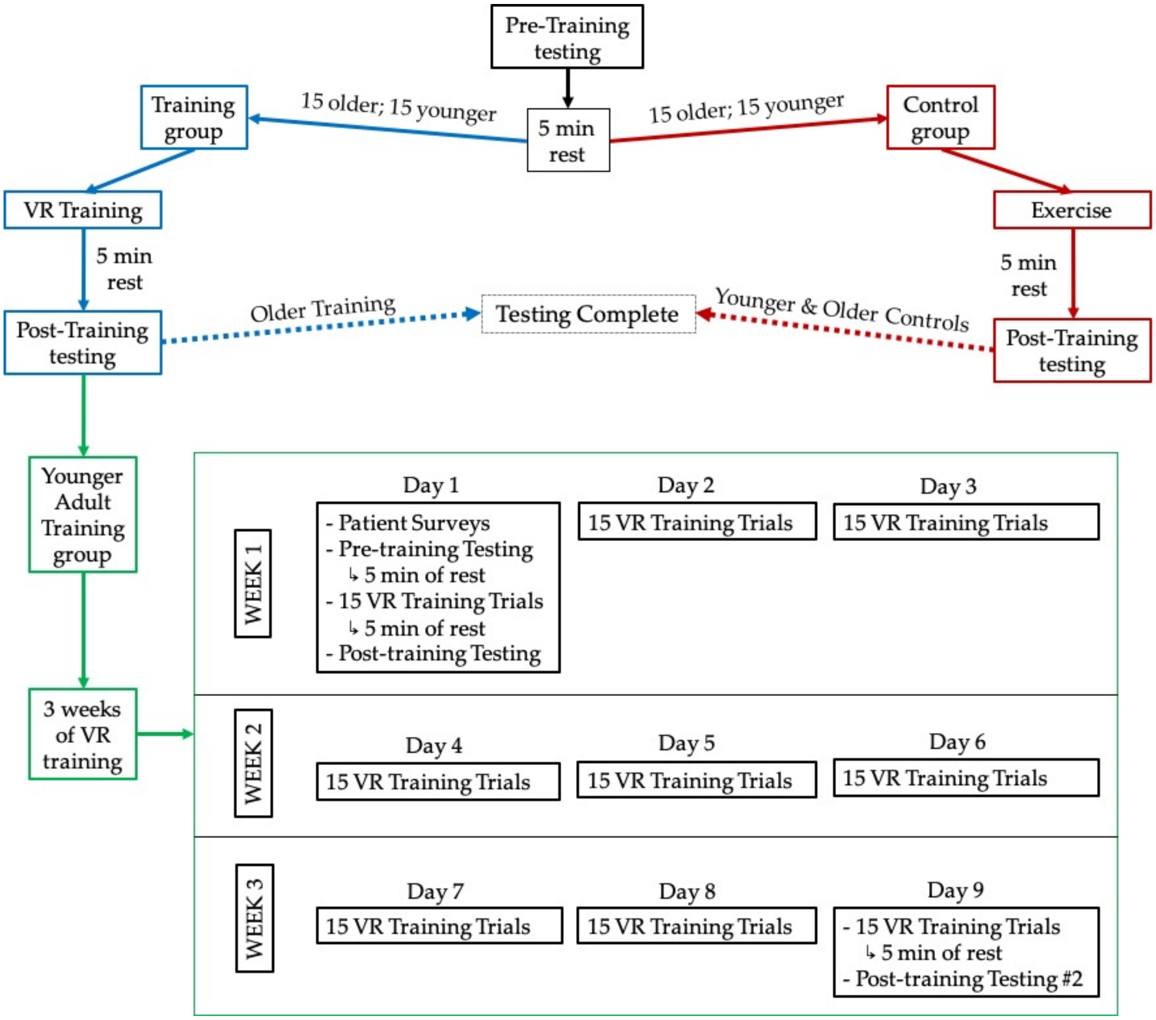

Figure 1. Schematic of Experimental Design.

Patient-Completed Surveys

Participant-completed surveys included the Activities-specific Balance Confidence (ABC) scale and the Medical Outcomes Survey Short Form 36 (SF-36). The ABC scale provides a measurement of confidence in completing balance-challenging activities of daily living. A lower score on the ABC represents a decreased balance confidence and is associated with balance-impairment (Cho et al., 2004) and falls (Lajoie & Gallagher, 2004). Question 1 of the ABC was found by Lajoie and Gallagher (2004) to be a significant predictor of falls and a main variable in their likelihood of falling equation. The SF-36 measures physical and mental health-related quality of life with higher scores indicating more favorable health states (Brazier et al., 1992). The ABC and SF-36 were electronically administered via Qualtrics to participants prior to arrival at the lab for pre-training testing.

Pre-/Post-Training Gait and Balance Tests

Functional Gait Assessment (FGA)

The FGA is a 10-item clinical gait test that asked participants to perform the following gait activities: walk at normal speeds, at fast and slow speeds, with vertical and horizontal head turns, with eyes closed, over obstacles, in tandem, backward, and while ascending and descending stairs (Wrisley et al., 2004).

Simple Reaction Time (SRT)

SRT is the length of time measured between the presentation of an unexpected stimulus and the onset of a response to that stimulus. Reaction time response increases with age and is further decreased among older adults who have fallen when compared with older adults who have not fallen (Lajoie & Gallagher, 2004). SRT was found to be the most significant predictor of falls and a crucial variable for input into the likelihood of falling equation presented by Lajoie & Gallagher (2004). The SRT was utilized in this study via computer mouse.

Berg Balance Scale (BBS) – Question 14

Question 14 of the BBS asked participants to stand on one leg as long as they can without holding. The question was scored from 0 (unable to try or needs assist) to 4 (able to lift leg independently and hold for >10s). Question 14 was found by Lajoie and Gallagher (2004) to be a significant predictor of falls and a main variable in their likelihood of falling equation.

AccWalker Smartphone Application

Spatiotemporal data and associated variability metrics were collected via the Accwalker app installed on an Android-based Google Pixel 1 phone (HTC, Xindian, New Taipei City, Taiwan). The phone was placed in a strap around the middle outer portion of the thigh. Participants were instructed to step in place for 70 seconds for 2 trials each of 2 separate conditions: eyes closed, and headshake. Specifically, the AccWalker was used to track thigh range of motion and stride time variability. Enhanced balance is characteristic of increased thigh range of motion and increased stride time variability.

BTrackS Balance Test

The BTrackS balance plate is a lightweight force plate specifically designed to objectively determine the CoP of foot forces during quiet standing. The protocol consisted of 3 static stance trials with participants standing as still as possible for 20 seconds with eyes closed, feet shoulder-width apart, and hands on hips. Poor postural control is defined as greater CoP movement (increased path length) and greater CoP rate of movement (increased mean velocity).

Real-world Obstacle Crossings

Retro-reflective markers were applied to the participants' body. A total of 24 markers were used and placed on the anterior superior and posterior superior iliac spines, iliac crests, medial and lateral knee and ankles, medial first and lateral fifth metatarsals, and the most anterior superior position on the shoe toe, and the calcanei. A real environment obstacle was set-up at the halfway mark (4m) along an 8m pathway. The obstacle was made of Masonite board, painted flat black and designed to easily tip over if contacted. The dimensions for the obstacle as 10 cm high, 100 cm wide, and 0.5 cm deep. A height of 10 cm is the average curb height. Each participant walked over the real environment obstacle for 10 successful non-contact trials (Figure 2).

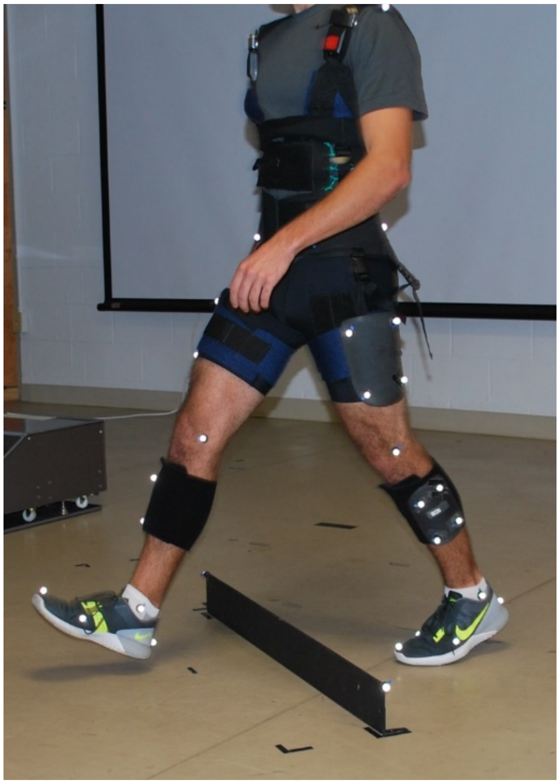

Figure 2. Participant Crossing the 10cm Real-world Obstacle.

Kinematic variable data was collected using Qualysis motion capture cameras (Gothenburg, Sweden). The data collected in the Qualysis software was resolved for landmark labeling, and then Visual 3D software (C-Motion, Germantown, MD) was used to import the data to organized data sets, and imported into MatLab (MathWorks, Natick, MA) to determine measures of foot placement and toe and heel clearance for both lead and trail limb using a custom script. Lead limb foot clearance was measured as the smallest distance between the toe marker and the obstacle during crossing. Trail limb foot clearance was measured as the smallest distance between the heel marker and the obstacle during crossing. Foot placement was measured as the horizontal distance between the toe marker and the obstacle for before-obstacle foot placement and as the horizontal distance between the heel marker and the obstacle for after-obstacle foot placement. Foot placement was measured before and after the obstacle for both the lead and trail limb.

Virtual Obstacle Course Environment

The virtual obstacle course was presented to participants using an immersive VR head mounted display – HTC Vive Pro (HTC, New Taipei City, Taiwan). The Vive Pro (Figure 3) is lightweight, portable, easy to set up, and very user friendly. It allows for a 400 ft^2 space to interact with a variety of virtual objects. The wireless nature allows participants to be unrestricted in their navigation of the virtual environment and the Vive Pro is integrative with additional vive trackers that were used to capture the movement of the feet and give real-time feedback about body position within the virtual space.

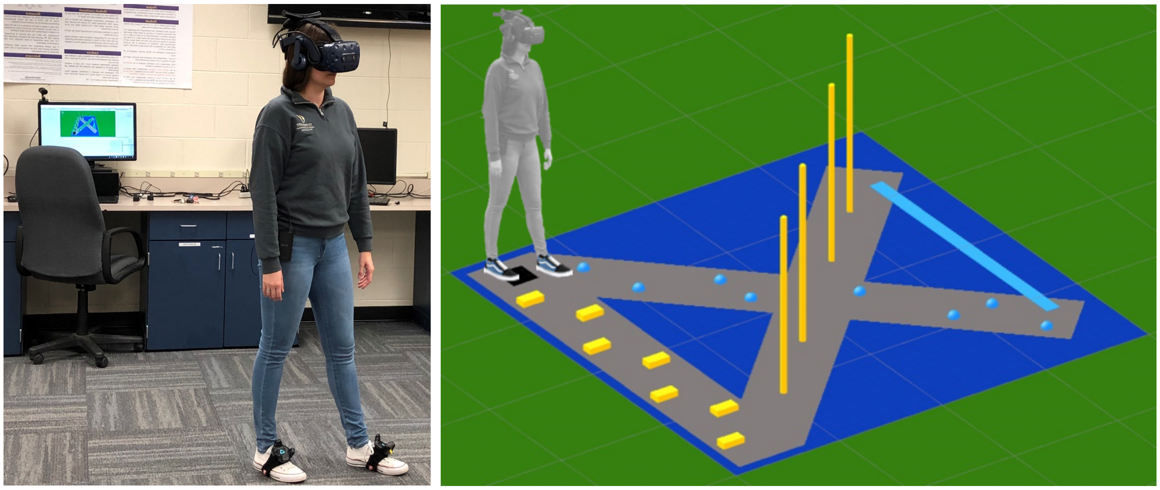

Figure 3. Depiction of VR Obstacle Course and Equipment Utilized to Portray Environment.

The virtual obstacle course environment consisted of a set of obstacles to be contacted or avoided by a set of virtual sneakers that mapped on to the real-time position of the participant's feet (Figure 3). The yellow obstacles were to be avoided, while the blue obstacles were to be contacted. The yellow obstacles were a set of rectangles meant to initiate a hopscotch-like motion where participants alternate which foot will step over the subsequent obstacle. Additionally, the yellow obstacles were a set of agility poles approximately 1.5 meters high, meant to initiate a mediolateral avoidance strategy, thus making the participant weave through the poles. The blue obstacles were a set of irregularly placed stepping stones and a tandem walking line that resembles a flat balance beam. If the yellow obstacles were contacted, a negative error tone played and the obstacle turned red; if the blue obstacles were contacted, they turned green and a positive click sound was heard.

All participants started and ended the obstacle course at the black square. They began the course with the yellow hopscotch obstacles, then moved to the yellow balance beams, then the blue tandem walking line, and finally the blue irregularly placed stepping stones. Participants were instructed on the various components of the course and were instructed as follows: "Complete the course as accurately as you can yet as quick as you feel comfortable." After each trial, the number of contacts of yellow obstacles, number of contacts of blue obstacles, and total time taken to complete the course was recorded. After all trials were complete, participants were asked to complete the NASA Task Load Index (NASA-TLX) to assess mental and physical workload.

Statistical Analyses

Purpose #1: Compare performance between older and younger adults in VR and in real-world gait and balance tests as a result of a single bout of VR training

Hypothesis 1a: Compared to the younger adult training group, the older adult training groups will show smaller and slower performance improvement in earlier in training.

In order to compare performance changes within the VR obstacle course environment between older and younger adults in the training groups, we collapsed the 15 training trials into 3 sets of 5 trials to capture the stages of training: early (average of trials 1-5), mid (average of trials 6-10), and late (average of trails 11-15). Three separate Group by Training Stage (2x3) repeated measures ANOVAs were conducted for each of the following: average number of foot-yellow obstacle contacts, average number of foot-blue obstacle contacts, and average time to complete the course.

Hypothesis 1b: Compared to controls, the training groups will show an improvement in in gait and balance tests from pre- to post-training testing with the older adult training group showing a greater extent of improvement than the younger adult training group.

In order to compare differences in functional gait and balance as a result of training vs. control between the two age groups, a series of Group by Time (4x2) mixed design MANOVAs were conducted. A Group by Time (4x2) mixed design MANOVA was conducted for AccWalker measures of range of motion, velocity, stride time, and variability. A Group by Time (4x2) mixed design MANOVA was conducted for BTrackS metrics of balance score, CoP path length, CoP mean velocity, and CoP root mean square differences in the mediolateral and anteroposterior directions. Lastly, two separate Group by Time (4x2) mixed design MANOVAs were conducted for real-world obstacle crossing metrics for foot placement metrics (before and after the obstacle for the lead and trail limb), and foot clearance metrics (radial clearance and peak elevation).

Purpose #2: Compare performance in VR with younger adults as a result of extended training duration

Hypothesis 2a: The younger adult training group will show improvements in performance within the VR environment in terms of decreased number of obstacles hit and decreased time to complete the course.

In order to compare changes in performance between VR training sessions, we collapsed the 9 training days into 3 sets of 3 days capture training duration: small (average of days 1-3), medium (average of days 4-6), and extended (average of days 7-9). A separate Group by Duration (1x3) repeated-measures ANOVA was calculated for each of the following: average number of foot-yellow obstacle contacts, average number of foot-blue obstacle contacts, and average time to complete the course.

Hypothesis 2b: The younger adult training group will show a further improvement in real-world gait and balance tests after 3 weeks of training from day 1 post-testing to day 9 post-testing.

In order to compare difference in functional gait and balance as a result of training, a Time (pre-test, post-test-1, post-test-2) repeated-measures MANOVA for AccWalker measures of range of motion, velocity, stride time, and variability was conducted. A Time (pre-test, post-test-1, post-test-2) repeated-measures MANOVA for BTrackS metrics of balance score, CoP path length, CoP mean velocity, and CoP root mean square differences in the mediolateral and anteroposterior directions was conducted. Lastly, two separate Time (pre-test, post-test-1, post-test-2) repeated-measures MANOVAs for real-world obstacle crossing metrics for foot placement metrics (before and after the obstacle for the lead and trail limb), and foot clearance metrics (radial clearance and peak elevation) were conducted.

Purpose #3: Evaluate clinical tests as pre-requisite measures for performance within the VR environment

Hypothesis 3: FGA score, simple reaction time, and ABC score will be significant predictors of performance within the VR environment

In order to predict performance in the VR obstacle course environment from patient-report surveys, three separate multiple regressions were calculated for each of the following: average number of foot-yellow obstacle contacts, average number of foot-blue obstacle contacts, and average time to complete the course. The ABC score and SF-36 score were entered as independent variables with age and gender as covariates.

In order to predict performance in the VR obstacle course environment from motor ability tests, three separate multiple regressions were calculated for each of the following: average number of foot-yellow obstacle contacts, average number of foot-blue obstacle contacts, and average time to complete the course. The FGA score, simple reaction time, and score for BBS Question 14 were entered as independent variables with age and gender as covariates.

Accommodations Due to Interruptions from COVID-19

On March 16, 2020, participant enrollment for this study was halted due to restrictions placed on human-subjects research with the emergence of COVID-19. Consequently, 13 of 15 younger training participants, 13 of 15 younger controls, 8 of 15 older adult training participants, and 1 of 15 older adult controls were collected. In addition, 3 of the 13 younger training participants only completed days 1-3 of training and did not complete a secondary post-test. As a result, and with the approval of my advisor, the following changes were made:

1. The older adult control group was dropped from hypotheses and analyses.
2. What was originally envisioned as Manuscript I and Manuscript II (Purpose 1 and 2, respectively) were combined into a single manuscript with two Experiments.
3. The statistical analyses were changed from MANOVAs to individual ANOVAs due to the lack of power from lack of overall number of subjects.
4. Within Experiment 1, two sets of ANOVAs were run for each the dependent variables of all four repeated tests: Simple Reaction Time, BTrackS Balance Test, Obstacle Crossing, and AccWalker. One set was run to compare the older training and younger training groups to examine the effect of age within training – due to the lack of number of older adults overall and lack of an

older adult control group. Another set was run to compare younger training and younger controls to examine the effect of training. To account for the changes in comparisons and statistical analyses in Experiment 1, three aims were established, each with their own hypothesis.

a. Aim 1 contains hypothesis 1a (now hypothesis 1) and compared performance between older and younger adults in VR.
b. The original hypothesis 1b was changed from "*Compared to controls, the training groups will show an improvement in gait and balance tests from pre- to post-training testing with the older adult training group showing a greater extent of improvement than the younger adult training group"* into Hypothesis 2 and 3 each under their own Aims.
c. Hypothesis 2 now states "The older adult training group would show a larger improvement in gait and balance tests from pre- to post-training testing compared to the younger adult training group" and examined the extent to which older adults improve in real-world gait and balance after a single bout of VR training compared to younger adults.
d. Hypothesis 3 now states "Compared to the younger adult control group, the younger adult training group will show further improvements in real-world gait and balance tests" and examined

the effect of training on real-world gait and balance within younger adults.

5. Within Experiment 2, only 10 of 13 of the younger training participants were analyzed as 3 did not complete the secondary post-test.

CHAPTER IV

THE EFFECT OF A NOVEL VIRTUAL REALITY OBSTACLE COURSE ON FUNCTIONAL MOBILITY IN YOUNGER AND OLDER ADULTS

Introduction

The United States population is rapidly aging, with approximately 16% of the population (52.4 million) 65 years of age and older (Roberts et al., 2018), which is estimated to increase to ~20% by 2030 (Ortman et al., 2014). With aging, the chance of falling significantly increases. Approximately 25% of older adults aged 65 years and older fall each year (Bergen et al., 2016). Falls are detrimental to older adults' quality of life as falling places them at a significant risk of injury – such as broken bones or head trauma, hospital stays, and increased chance of morbidity (Alexander et al., 1992; Bergen et al., 2016; King & Tinetti, 1995; Sterling et al., 2001; Tinetti et al., 1988). Injuries due to falling can lead to a decrease in physical capability (Rubenstein, 2006), subsequently decreasing mobility and physical activity (Tinetti et al., 1988), furthering the risk of adverse long-term health-related outcomes (King & Tinetti, 1995).

The most common risk factors for falling in older adults are related to gait and balance. Approximately 55% falls are due to slips, trips, and displaced center of gravity, while 31% are due to poor mobility, balance, cognition, or sensory impairment (King & Tinetti, 1995). Older adults have a decreased ability to control their balance and walking (Maki et al., 1994; Rubenstein, 2006; Tinetti et al., 1988) due to age-related changes in reaction time (Lajoie & Gallagher, 2004), muscle mass/strength (Goodpaster et al., 2006; Tinetti & Kumar, 2010), and attention/cognitive ability (Mirelman et al., 2012).

Fall-risk factors related to gait include decreased gait speed, step length, step width, and poor adaptations to obstacle perturbations (Berg et al., 1997; Chen et al., 1991, 1994; Muir et al., 2015). Thirty-four percent of falls in older adults are the result of a trip, with the majority resulting from poor obstacle negotiation (Berg, Alessio, Mills, & Tong, 1997). Poor adaptations to obstacle perturbations are characterized by a decreased ability to alter foot trajectory within the obstacle crossing step (Berg et al., 1997). Older adults tend to exhibit a foot trajectory that is closer to the obstacle before, during, and after crossing (Chen et al., 1994; Chen et al., 1991; Muir et al., 2015), thus increasing the risk of obstacle contact.

Fall-risk factors related to balance include decrements in postural control. Postural control may be examined by tracking the Center of Pressure (CoP)—a metric that quantifies the changing location of the average location of foot pressure. Examples of decrements in postural control include a larger maximal displacement and maximal velocity of COP (Muir et al., 2013), larger displacement of the CoP in the mediolateral direction (Maki et al., 1994; Swanenburg et al., 2010), and increased CoP velocity in the anteroposterior direction (Berg, Maki, et al., 1992). Thus, examining gait, balance, and mobility factors may give an insight into fall risk, and positively modifying these factors may help reduce falling in older adults.

In order to mitigate these fall-risk factors, some fall prevention programs have been developed that have taken a variety of approaches, including physical activity, vitamin supplements, and multifactorial methodology (Chase et al., 2012; Guirguis-Blake et al., 2018). However, implementing these programs provides a variety of financial, resource, and social challenges that may hinder the efficacy of the program (Child et al., 2012; McMahon et al., 2018; Shier et al., 2016). Virtual reality (VR) may be an appropriate method to mitigate these issues.

VR is a novel method that provides opportunities for training that can be motivational and engaging, cost-effective, and resource-efficient, which may lead to greater efficacy of fall prevention programs. Previous research has shown the benefits of gait and balance training with VR elements in a variety of populations with aging and disease, such as patients with Parkinson's, multiple sclerosis, acute and chronic post-stroke hemiplegia, traumatic brain injury, and cerebral palsy (Cano Porras et al., 2018). These benefits of training with VR elements has resulted in improvements of balance, gait spatiotemporal measures, and kinematics – such as walking speed, stride length, walking endurance, balance control, mobility, and obstacle crossing (Baram & Miller, 2006; Cano Porras et al., 2018; Cho et al., 2012; Darter & Wilken, 2011; Gates et al., 2012; Jaffe et al., 2004; Lee et al., 2014; Liao et al., 2015; LoJacono et al., 2018; Mirelman et al., 2011, 2016a; Shema et al., 2014a; Sin & Lee, 2013). VR has also been suggested to be an advantageous environment for learning motor skills because VR can provide task-specific information, augmented feedback, and repetition in a tailored and specific manner (Wulf, 2007), while allowing participants to engage in motor skill learning in a motivational and cognitively engaging way (Cano Porras et al., 2018; Howard, 2017). Moreover, training with VR elements has shown to improve obstacle crossing with a single bout of training (LoJacono et al., 2018), and has been shown to be more effective relative to traditional training in improving gait spatiotemporal measures (Jaffe et al., 2004; Mirelman et al., 2011, 2011).

Despite the promising initial results of VR as an advantageous and more effective training tool, there are a few unknowns. First, there is a lack of normative data from healthy older adults without physical and neurological impairments in regard to how VR training may affect this population. Due lack of normative data, it is unclear the extent to which VR training may be used as a preventive tool for those who are cognitively and physically healthy. Second, many previous studies have used non-immersive VR environments while on a treadmill. Treadmills constrain participants to interact with the VR environment to primarily the anteroposterior direction, thus limiting training and minimizing the mediolateral direction – a crucial direction in avoidance strategies used in our everyday natural environments. In addition, treadmills do not allow participants to vary their speed in order to be successful in their obstacle avoidance strategies. The alternative solution is an immersive VR headset that allows participants to freely engage with a virtual environment while walking overground, but it is unknown how participants may respond to gait and balance training in an immersive VR headset. Thus, this study aimed to determine the extent to which younger and older adults performed within an overground VR obstacle course environment utilizing an immersive VR headset. Lastly, it is unknown the extent to which repeated training within a VR environment may affect performance within the environment and transfer to and improvement of real-world gait and balance. Thus, this study aimed to examine the effect of training duration and to determine the extent to which gait and balance is improved and if a ceiling effect occurs.

To accomplish these aims, this study consisted of two experiments. Experiment 1 measured the performance of both healthy younger and older adults within a novel VR obstacle course environment and the extent to which real-world gait and balance tests improved as a result of a single bout of VR obstacle course training. Experiment 2 examined the changes in performance of healthy young adults over three weeks of VR obstacle course training and the further effects of extended training duration on real-world gait and balance.

Experiment 1

The aims of this experiment were three-fold: (Aim 1) to compare performance between older and younger adults in VR, (Aim 2) to examine the extent to which older adults improve in real-world gait and balance after a single bout of VR training compared to younger adults, and (Aim 3) to examine the effect of training on real-world gait and balance within younger adults. Our hypotheses were: (1) compared to the younger adult training group, the older adult training group would show smaller and slower performance improvement in earlier in training, (2) the older adult training group would show a larger improvement in gait and balance tests from pre- to post-training testing compared to the younger adult training group, and (3) compared to the younger adult control group, the younger adult training group will show further improvements in real-world gait and balance tests.

Methods

Participants

A total of 34 participants were recruited for this study and split into 3 groups: Younger Control (YC; N =13), Younger VR Training (YT; N = 13), and Older VR Training (OT; N = 8). Participants were either between the ages of 18-35 years or 60 years and older, had normal or corrected-to-normal vision, a Body Mass Index of less than 30, and the ability to walk for 15 minutes without the use of an assistive device. All participants reported no current musculoskeletal injuries, no diagnosed cognitive, neurological, or muscular disorders, and no current pregnancies. Participant demographics are presented in Table 1.

Table 1. Participant Demographics. All variables represented as Mean (SD).

Group	**Age (years)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**
Younger Control (YC)	21.7 (1.0)	168.8 (9.0)	69.2 (13.6)	24.2 (3.8)
Younger VR Training (YT)	22.1 (2.5)	168.3 (8.6)	68.3 (10.8)	24.1 (3.3)
Older VR Training (OT)	67.0 (4.4)	164.6 (5.9)	63.8 (11.4)	23.4 (2.5)

Experimental Design

This study utilized a pre-test/post-test design. Pre- and post-testing included a Simple Reaction Time (SRT) test, Balance Tracking System (BTrackS™) Balance Test (BBT), real-world obstacle crossings, and a dynamic balance test using a smartphone application (AccWalker). In between testing sessions, the YT and OT groups completed training within the custom-built dynamic virtual reality obstacle course. The YC group completed 15 minutes of walking to control for physical activity duration (Figure 4). All procedures were approved by the University's Institutional Review Board.

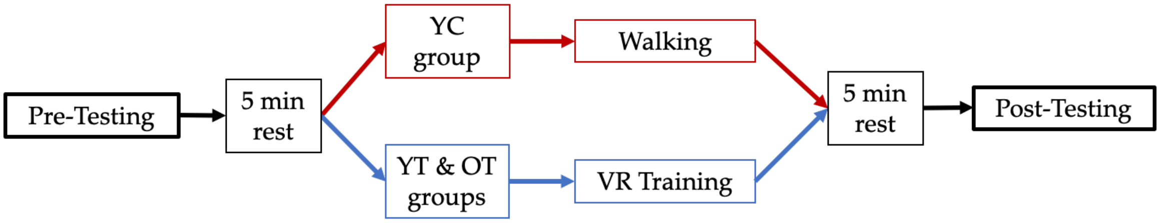

Figure 4. Experimental Design.

Experimental Procedure

Upon arrival to the lab, participants gave informed consent. Demographic information was collected, and height and weight were measured. Participants then began the pre-test. The SRT task asked participants to observe a stoplight on a computer screen. Once the stoplight shifted from red to green, participants were asked to left-click an on-screen button with their computer mouse as quickly as possible in response. Participants completed five trials. The BBT had participants to step onto the BTrackS balance board with their feet shoulder-width apart, hands on hips, looking straight forward. Participants then closed their eyes for 20 seconds of quiet standing per trial for a total of three trials. Center of Pressure (CoP) data were collected at 25 Hz.

Participants then completed 10 crossings of a real-world obstacle with their dominant foot every time. Dominant foot was determined via the question, "If you were to kick a ball for distance, which foot would you use to kick with?" The obstacle was made of Masonite board with L-brackets, painted flat black, and designed to tip over easily if contacted. The obstacle was 10cm high (average sidewalk curb height), 100cm wide to ensure participants stepped over with both feet, and 0.5cm thick to ensure a minimal fall risk if contacted and tipped over. It was placed halfway in an 8-meter walkway to give appropriate distance to plan the approach before the obstacle and recovery after the obstacle. Retroreflective markers were placed bilaterally on the toes (most anterior-superior position of the shoe), heels, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, anterior superior iliac spines, posterior superior iliac spines, and iliac crests. Qualysis Track Manager (Qualysis AB, Gothenburg, Sweden) was used to track the position of the retroreflective markers at 100 Hz during the real-world obstacle crossing task. The positional data were then exported and transformed to obtain foot placement and foot clearance metrics.

The last task during the pre-testing session was the dynamic balance test with the AccWalker smartphone app, which has been shown to be a reliable and valid tool to measure neuromotor control (Kuznetsov et al., 2018). It was implemented on a Google Pixel 1 (HTC, Xindian, New Taipei, Taiwan), which was strapped to the lateral midpoint of the right thigh. AccWalker records temporal and spatial data of the thigh during a stepping-in-place task. Participants stepped in place to the beat of a metronome for 10 seconds and then maintained that stepping rhythm for an additional 60 seconds. Participants stepped in place for a total of 70 seconds per trial for 6 trials – 2 trials in each condition: Eyes open, Eyes Closed, and while shaking their head (Head Shake). The Eyes

Closed examines the role of vision and the Head Shake condition examines the role of the vestibular system on balance control (Kuznetsov et al., 2018).

After completing the pre-test, participants rested in a sitting position for 5 minutes. After resting, the younger control group continuously walked overground for 15 minutes in an open area. The training groups (YT and OT) participated in our dynamic VR obstacle course (Figure 5). The VR obstacle course was created and implemented using Unity Game Engine (Unity Technologies, San Francisco, CA, USA) and displayed in the HTC Vive (HTC, New Taipei City, Taiwan). Additionally, HTC Trackers were placed on the participant's feet and were utilized to display virtual sneakers that map onto the participant's foot in VR to give real-time feedback of foot position (Figure 5). The VR obstacle course contained a variety of different obstacles. Participants were asked to avoid the yellow obstacles and step on the blue obstacles. All participants were told to start and stop in the black square and were told to follow the following course format: (1) step over the yellow bricks in front of them with alternating feet, (2) turn left and weave in and out of the yellow agility poles, (3) turn right and walk across the flat blue balance beam with one foot in front of the other, and (4) turn right and step on each of the blue stepping stone back to the black square. Participants were asked to complete the VR obstacle course as accurately as they can yet as quick as they feel comfortable If a yellow obstacle was contacted, it subsequently turned red and a negative error auditory tone was heard. If a blue obstacle was contacted, it turned green and a positive click tone was heard. At the end of each trial, a pop-up appeared on screen informing the participant of how many yellow and blue obstacles were each contacted. Both YT and OT groups completed 15 trials of the dynamic VR obstacle course with 30 seconds of rest in between each trial.

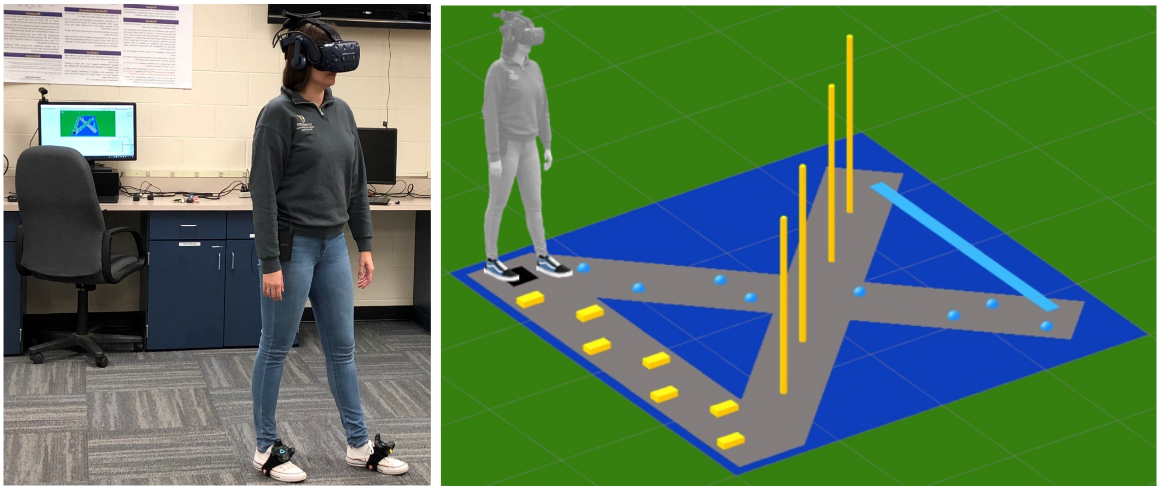

Figure 5. Depiction of VR Obstacle Course and Equipment Utilized to Portray Environment.

After the VR training (YT and OT groups) or walking (young control group), all groups rested for another 5 minutes in a seated position. While resting, they completed the NASA Task Load Index (TLX) to measure workload in 5 domains: temporal, physical, mental, performance, and frustration. All groups then completed the post-test that consisted of a repeat of the tasks used in the pre-test: the SRT, BBT, 10 real-world obstacle crossings, and AccWalker tasks.

Data Reduction

SRT was determined via averaging all 5 trials to obtain an average SRT value per testing session. Raw CoP positional data were collected from the BBT. A custom MATLab (Mathworks, Natwick, MA, USA) script was created to transform the raw CoP data into the following variables: Path Length, CoP SD_{ML} (mediolateral), CoP SD_{AP} (anteroposterior), Resultant Velocity Mean, Resultant Velocity SD, and Sample Entropy (SampEn) of CoP Resultant Velocity.

Real-world obstacle crossing variables of foot clearance and foot position were obtained using another custom MATLab script that has previously been detailed (LoJacono et al., 2018). The foot placement metrics obtained were foot position before the obstacle and foot position after the obstacle for both the lead foot and trail foot. Foot position before the obstacle was determined as the horizontal distance between the toe marker and the obstacle during the single stance phase before crossing for each foot. Foot position after the obstacle was determined as the horizontal distance between the heel marker and the obstacle during single stance phase after crossing for each foot. Foot clearance metrics obtained were radial clearance and peak elevation for both the lead foot and the trail foot. Radial clearance is defined as the closest distance from a foot marker to the obstacle within the obstacle crossing trajectory. For the lead foot, the distance from the heel marker was used and for the trail foot the distance from the toe marker was used, as these markers are often the lowest and closest markers to the obstacle during the crossing step. Peak elevation was determined by the highest point of the trajectory during the crossing step. Lastly, stride length over the obstacle for each foot was determined by examining the distance between the position of the toe before crossing the obstacle and the position of the heel of the same foot after crossing the obstacle.

AccWalker temporal and spatial variables of Stride Time, Stride Time Coefficient of Variation (Stride Time CV), Thigh Range of Motion (Thigh ROM), Peak Thigh

Flexion SD, and Peak Thigh Return Velocity SD were obtained using another custom MATLab script previously described (Kuznetsov et al., 2018). Peak thigh flexion SD was determined by the phone angle at the peak of thigh flexion, whereas peak thigh return velocity SD was determined by the peak velocity during the leg's return to stance after lifting from the ground (Kuznetsov et al., 2018). Each variable was calculated per trial. Both trials were averaged together for each condition to produce an overall variable per condition for session.

Statistical Analyses

To address Hypothesis 1, the 15 training trials on day 1 were collapsed into 3 sets of 5 trials to capture the stages of training: Early (average of trials 1-5), Mid (average of trials 6-10), and Late (average of trails 11-15). Two separate Group (YT, OT) by Training Stage (Early, Mid, Late) repeated-measures ANOVAs were conducted for each of the following: average number of yellow obstacle contacts and average time to complete the course. To address Hypothesis 2, a series of Group (YT vs. OT) by Test (pre-test vs. post-test) repeated-measures ANOVAs were conducted on each of the metrics of the four repeated tasks: SRT, BBT, Obstacle Crossing, and AccWalker. To account for unequal sample sizes, Cohen's d_z effect sizes were calculated to quantify the effect of group assignment. Cohen's d_z effect sizes can be classified as large (≥ 0.80), medium (≥ 0.50), small (≥ 0.20), and minimal (< 0.20). To address Hypothesis 3, a series of Group (YC vs. YT) by Test (pre-test vs. post-test) repeated-measures ANOVAs were conducted for each of the metrics of the four repeated tasks: SRT, BBT, Obstacle

Crossing, and AccWalker. Alpha level was set a priori at 0.05 for all analyses. A Greenhouse-Geisser correction for the *F*-tests and follow-up pairwise comparisons with Bonferroni corrections were applied when applicable.

Results

Aim 1: Compare Performance Between Older and Younger Adults in VR

There was a significant main effect of Time for training stage [$F(1.125, 21.375) = 15.73$, $p < 0.0001$]. Follow-up tests showed a significant reduction in time (i.e., faster performance) between Early to Mid (p =0.003), Mid to Late ($p = 0.038$), and Early to Late Training Stages ($p = 0.002$; Figure 6). There was not a significant main effect of Group ($F_{1,19} = 3.632$, $p = 0.072$) or Interaction [$F(1.125, 21.375) = 0.623$, $p = 0.457$]. For further transparency, a trial-by-trial graph is provided in Figure 6A. The averages for the Early, Mid, and Late stages for both age groups are shown in Figure 6B, for which the statistics were run. Effect sizes are reported in Table 2. No significant main effects of Group, Time, or Interaction were observed for yellow obstacle contacts ($p > 0.05$).

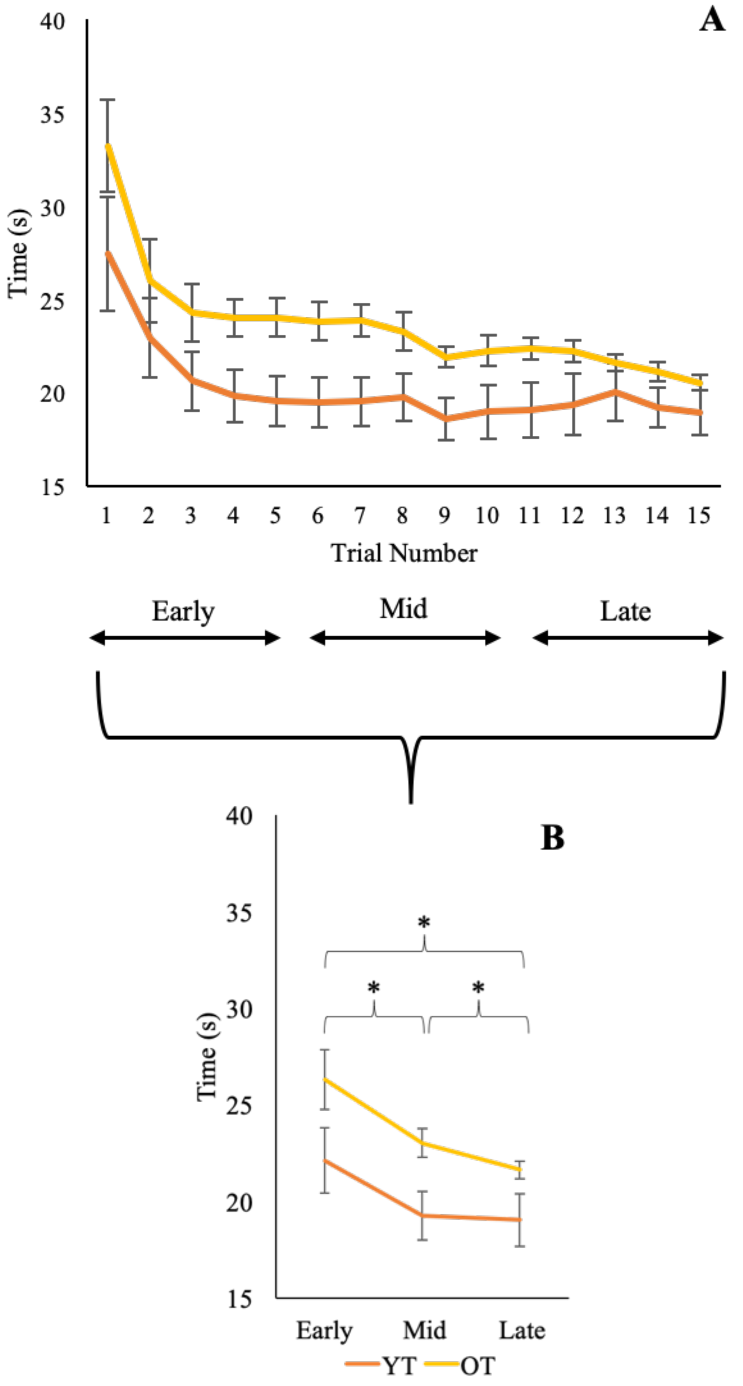

Figure 6. Trial-by-trial (A) and Average Time per Stage (B) to Complete VR Course for OT and YT. (*) = significant difference in Test

Table 2. Time to Complete VR Obstacle Course During Each Training Stage. Values represented as Mean(SD). Symbols ($*^{\Diamond\ddagger}$) indicate significance between training stages.

Group	**Time (s)**			**Cohen's d_z**	
	Early	*Mid*	*Late*	*Early/Mid*	*Mid/Late*
YT	22.10 (6.06)	19.25 (4.57)	19.02 (4.93)	-0.716	-0.196
OT	26.29 (4.39)	23.01 (2.11)	21.63 (1.28)	-1.278	-0.927
Overall	23.70 (5.75) $*^{\Diamond}$	20.68 (4.20) $*^{\ddagger}$	20.01 (4.10) $^{\ddagger\Diamond}$	--	

Aim 2: Examine the Extent to which Older Adults Improve in Real-world Gait and Balance After a Single Bout of VR Training Compared to Younger Adults

Simple Reaction Time

There was a significant interaction ($F_{1,19} = 4.812$, $p = 0.041$, $\eta_p^2 = 0.202$), such that there was a significant increase in SRT (i.e., worse performance) at post-test for OT (0.377 ± 0.078s) compared to YT (0.278 ± 0.043s, $p = 0.001$; Figure 7). Cohen's d_z effect sizes revealed a medium negative effect for YT (-0.633) from pre-test to post-test and a small positive effect for OT (+0.375).

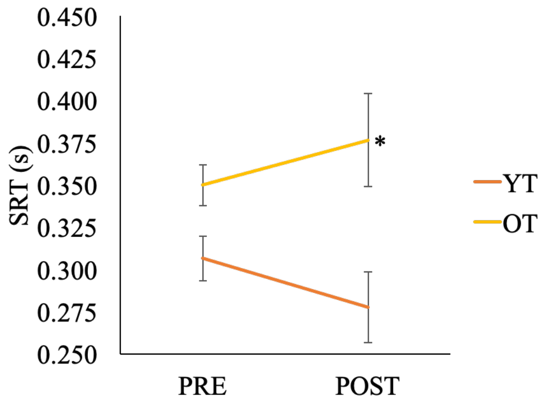

Figure 7. Changes in Simple Reaction Time (SRT) from Pre-test to Post-test for OT and YT. (*) = significant difference in Test.

BBT

For path length, there was a significant interaction ($F_{1,19} = 7.185$, $p = 0.015$, Wilks'$\Lambda = 0.726$, $\eta_p^2 = 0.274$), with path length significantly increasing (i.e., worse performance) from pre-test and post-test for OT ($p = 0.034$), but not YT ($p = 0.169$; Figure 8A). For CoP$_{AP}$ SD, there was a significant main effect of Group ($F_{1,19} = 6.291$, $p = 0.021$, $\eta_p^2 = 0.249$), with CoP$_{AP}$ SD significantly higher (i.e., worse performance for OT compared to YT ($p = 0.021$; Figure 8B). For SampEn, there was a significant interaction ($F_{1,19} = 5.149$, $p = 0.035$, Wilks'$\Lambda = 0.787$, $\eta_p^2 = 0.213$), with a significant decrease between pre-test and post-test for OT ($p = 0.004$), but not YT ($p = 0.600$; Figure 8C). There were no significant main effects or interactions for CoP$_{ML}$ SD, resultant velocity, or resultant velocity SD ($p > 0.05$). Effect sizes for BBT variables are reported in Table 3.

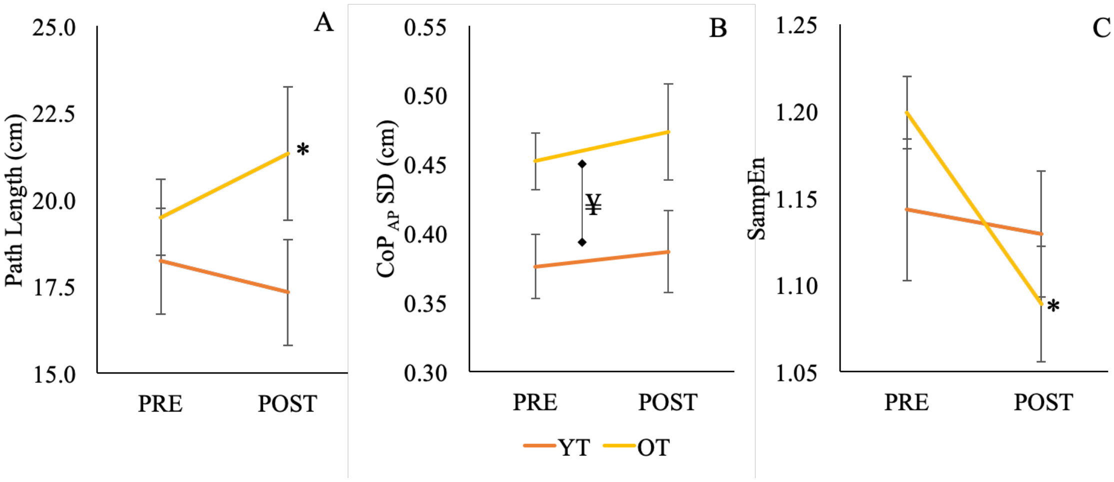

Figure 8. Significant BBT Metrics from Pre-test to Post-test for OT and YT. Variables include Path length (A), CoP$_{AP}$ SD (B), and SampEn (C). (*) = significant difference in Test, (¥) = significant difference in Group.

Table 3. Summary of Significant Variables for BBT Task for OT and YT. Symbols indicate main effects of Group (¥) and Interaction (§) at $\alpha = 0.05$. Cohen's d_z interpreted as a strong effect in bold (≥ 0.8), medium effect in bold italics (≥ 0.5), small effect (≥ 0.2), and minimal effect (< 0.2).

Variable	**Group**	**Pre-test**	**Post-test**	**Delta Score**	**Cohen's d_z**
§ Path Length (cm)	*YT*	18.23 (5.49)	17.33 (3.94)	-0.90 (2.24)	-0.402
	OT	19.49 (4.31)	21.33 (5.42)	1.84 (2.33)	***0.790***
	Overall	*18.71 (4.99)*	*18.85 (4.85)*	*0.143 (2.60)*	
¥ CoP_{AP} SD (cm)	*YT*	0.376 (0.084)	0.387 (0.073)	0.011 (0.066)	0.163
	OT	0.452 (0.084)	0.473 (0.098)	0.021 (0.109)	0.195
	Overall	0.405 (0.090)	0.420 (0.092)	0.015 (0.082)	
§ SampEn	*YT*	1.143 (0.147)	1.129 (0.130)	-0.014 (0.101)	-0.138
	OT	1.199 (0.059)	1.089 (0.094)	-0.110 (0.082)	**-1.340**
	Overall	*1.164 (0.122)*	*1.114 (0.117)*	*-0.051 (0.104)*	

Obstacle Crossing

For foot clearance relative to the lead foot, there were no significant main effects or interaction for either radial clearance or peak elevation ($p > 0.05$). For trail foot clearance, there was a significant main effect of Group for radial clearance ($F_{1,19} = 4.720$, $p = 0.043$, $\eta_p^2 = 0.199$), with radial clearance higher for OT than YT ($p = 0.043$; Figure 9A). There was also a significant main effect of Group for peak elevation ($F_{1,19} = 5.297$, $p = 0.033$, $\eta_p^2 = 0.218$), with peak elevation higher for OT than YT ($p = 0.033$; Figure 9B). For foot position relative to the lead foot, there was a significant main effect of Test for position before the obstacle ($F_{1,19} = 15.724$, $p = 0.001$, Wilks'$\Lambda = 0.547$, $\eta_p^2 = 0.453$), with an increase from pre-test to post-test ($p = 0.001$; Figure 9C). There was not a significant main effect or interaction for position after the obstacle of the lead foot ($p > 0.05$). For the trail foot position, there was a significant main effect of Test for position before the obstacle ($F_{1,19} = 8.542$, $p = 0.009$, Wilks'$\Lambda = 0.690$, $\eta_p^2 = 0.310$), with an increase from pre-test to post-test ($p = 0.008$; Figure 9D). There was not a significant main effect or interaction for position after the obstacle of the trail foot ($p > 0.05$) Relative to stride length for the lead foot, there was a significant main effect of Test ($F_{1,19} = 14.112$, $p = 0.001$, Wilks'$\Lambda = 0.574$, $\eta_p^2 = 0.426$), with an increase from pre-test to post-test ($p = 0.001$; Figure 9E). For the trail foot, there was not a significant main effect or interaction for stride length ($p > 0.05$). Effect sizes for foot clearance variables are reported in Table 4.

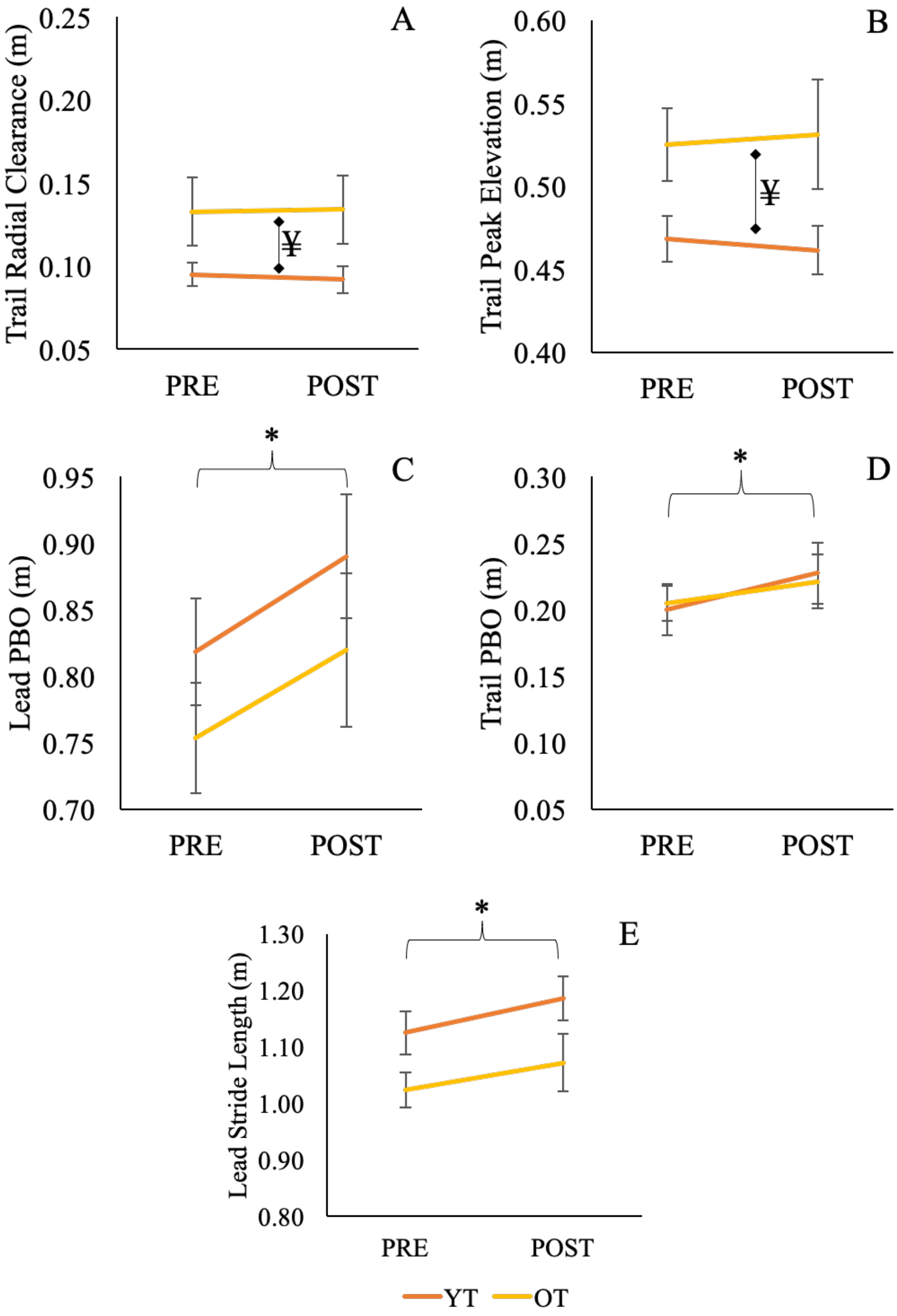

Figure 9. Significant Obstacle Crossing Metrics from Pre-test to Post-test for OT and YT. Variables include trail foot clearance metrics of radial clearance (A) and peak elevation (B), foot position before the obstacle (PBO) for Lead (C) and Trail foot (D), and Lead foot stride length (E). (*) = significant difference in Test, (¥) = significant difference in Group.

Table 4. Summary of Significant Variables for the Obstacle Crossing Task for OT and YT. Variables include radial clearance (RC), peak elevation (PE), position before obstacle (PBO), and stride length (SL). Symbols indicate main effects of Group (¥) and Test (‡) at $\alpha = 0.05$. Cohen's d_z interpreted as a strong effect in bold (≥ 0.8), medium effect in bold italics (≥ 0.5), small effect (≥ 0.2), and minimal effect (< 0.2).

	Variable	Group	Pre-test	Post-test	Delta Score	Cohen's d_z
Foot Clearance	**¥ RC – Trail (m)**	*YT*	0.095 (0.026)	0.092 (0.029)	-0.003 (0.013)	-0.235
		OT	0.133 (0.058)	0.134 (0.058)	0.001 (0.016)	0.072
		Overall	*0.109 (0.044)*	*0.108 (0.046)*	*-0.001 (0.014)*	
	¥ PE – Trail (m)	*YT*	0.468 (0.050)	0.461 (0.052)	-0.007 (0.029)	-0.241
		OT	0.525 (0.062)	0.531 (0.094)	0.006 (0.035)	0.182
		Overall	*0.341 (0.175)*	*0.337 (0.171)*	*-0.004 (0.024)*	
Foot Position	**‡ PBO – Lead (m)**	*YT*	0.818 (0.146)	0.890 (0.168)	0.072 (0.060)	**1.190**
		OT	0.753 (0.118)	0.820 (0.164)	0.066 (0.100)	***0.661***
		Overall	*0.793 (0.137)*	*0.863 (0.166)*	*0.070 (0.076)*	
	‡ PBO – Trail (m)	*YT*	0.200 (0.069)	0.227 (0.082)	0.027 (0.029)	**0.938**
		OT	0.205 (0.037)	0.221 (0.057)	0.017 (0.040)	0.418
		Overall	*0.202 (0.058)*	*0.225 (0.072)*	*0.023 (0.033)*	
Stride Length	**‡ SL – Lead (m)**	*YT*	1.125 (0.137)	1.186 (0.142)	0.061 (0.050)	**1.228**
		OT	1.023 (0.088)	1.072 (0.143)	0.049 (0.085)	***0.573***
		Overall	*1.086 (0.129)*	*1.142 (0.150)*	*0.056 (0.063)*	

AccWalker

For the Eyes Open condition, there was a significant interaction for stride time ($F_{1,19} = 6.085$, $p = 0.023$, Wilks'$\Lambda = 0.757$, $\eta_p^2 = 0.243$), decreasing (i.e., better performance) from pre-test to post-test for YT ($p < 0.0001$), but not OT ($p = .407$; Figure 10A). For stride time CV, there was a significant main effect of Group ($F_{1,19} = 10.306$, $p = 0.005$, $\eta_p^2 = 0.352$), showing OT had higher values relative to YT ($p = 0.005$; Figure 10B). There were no significant main effects or interactions for thigh ROM, peak thigh flexion SD, or peak thigh return velocity for the Eyes Open condition ($p > 0.05$). For the

Eyes Closed condition, there was a significant interaction for stride time CV ($F_{1,19}$ = 5.449, p = 0.031, Wilks'Λ = 0.777, η_p^2 = 0.223), revealing higher values (i.e., worse performance) at pre-test for OT than YT (p = 0.004), but not post-test (p = 0.101; Figure 10C). There were no significant main effects or interactions for stride time, thigh ROM, peak thigh flexion SD, or peak thigh return velocity for the Eyes Closed condition (p > 0.05). For the Head Shake condition, there was a significant interaction for stride time CV time ($F_{1,19}$ = 4.730, p = 0.042, Wilks'Λ = 0.801, η_p^2 = 0.199), showing higher values at pre-test for OT than YT (p = 0.014), but not post-test (p = 0.290; Figure 10D). Effect sizes for AccWalker variables are reported in Table 5.

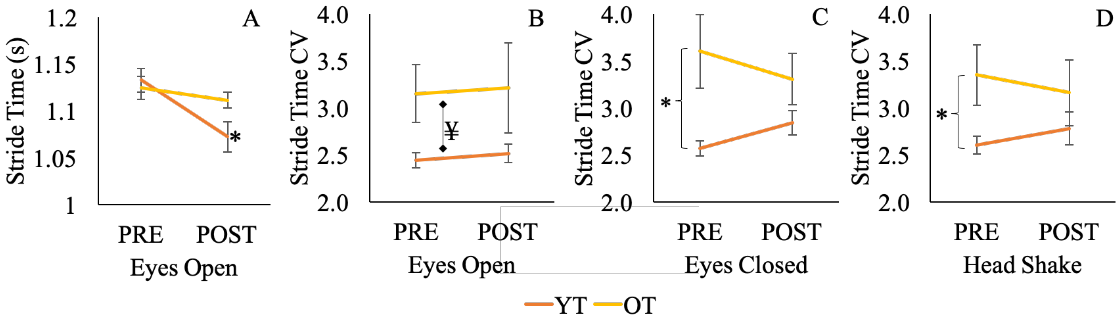

Figure 10. Significant AccWalker Metrics from Pre-test to Post-test for OT and YT. Conditions represented as Eyes Open (EO), Eyes Closed (EC), and Head Shake (HS). Variables are Stride Time EO (A), stride time CV in the conditions of EO (B), EC (C), and HS (D). (*) = significant difference in Test, (¥) = significant difference in Group.

Table 5. Summary of Significant Variables for the AccWalker Task for OT and YT. Conditions are Eyes Open (EO), Eyes Closed (EC), and Head Shake (HS). Symbols indicate main effects of Group (¥) and Interaction (§) at $\alpha = 0.05$. Cohen's d_z interpreted as a strong effect in bold (≥ 0.8), medium effect in bold italics (≥ 0.5), small effect (≥ 0.2), and minimal effect (< 0.2).

Variable	Group	Pre-test	Post-test	Delta Score	Cohen's d_z
§ Stride Time EO	*YT*	1.133 (0.046)	1.072 (0.059)	-0.060 (0.050)	**-1.192**
	OT	1.124 (0.034)	1.111 (0.025)	-0.013 (0.024)	***-0.528***
	Overall	*1.129 (0.041)*	*1.087 (0.051)*	*-0.042 (0.048)*	
¥ Stride Time CV EO	*YT*	2.441 (0.284)	2.515 (0.352)	0.074 (0.376)	0.196
	OT	3.149 (0.870)	3.210 (1.357)	0.060 (1.759)	0.034
	Overall	*2.711 (0.661)*	*2.780 (0.916)*	*0.069 (1.080)*	
§ Stride Time CV EC	*YT*	2.572 (0.294)	2.844 (0.465)	0.273 (0.333)	**0.820**
	OT	3.606 (1.110)	3.307 (0.773)	-0.299(0.785)	-0.381
	Overall	*2.966 (0.865)*	*3.021 (0.626)*	*0.055 (0.602)*	
§ Stride Time CV HS	*YT*	2.604 (0.342)	2.780 (0.633)	0.177 (0.452)	0.390
	OT	3.353 (0.910)	3.163 (0.986)	-0.190 (0.177)	**-1.076**
	Overall	*2.889 (0.706)*	*2.926 (0.786)*	*0.037 (0.409)*	

Aim 3: Examine the Effect of Training on Real-world Gait and Balance within Younger Adults

Simple Reaction Time

There was a significant main effect of Test ($F_{1,24} = 4.438$, $p = 0.048$, Wilks' $\Lambda = 0.847$, $\eta_p^2 = 0.153$), showing a decrease (i.e., better performance) from pre-test to post-test ($p = 0.048$).

BBT

For CoP_{ML} SD, there was a significant main effect of Group ($F_{1,24} = 5.094$, $p = 0.033$, $\eta_p^2 = 0.175$), revealing that YC had higher values (i.e., worse performance) relative to YT ($p = 0.033$). There were no significant main effects or interaction for path length, CoP_{AP} SD, resultant velocity, resultant velocity SD, or SampEn ($p > 0.05$).

Obstacle Crossing

For the lead foot clearance, there was a significant main effect of Test for radial clearance ($F_{1,24} = 6.997$, $p = 0.014$, Wilks' $\Lambda = 0.774$, $\eta_p^2 = 0.226$), showing a significant decrease from pre-test to post-test ($p = 0.014$; Figure 11A). There were no significant effects or interaction for peak elevation for the lead foot ($p > 0.05$). For the trail foot clearance, there was a main effect of test for peak elevation ($F_{1,24} = 9.621$, $p = 0.0105$ Wilks' $\Lambda = 0.14$, $\eta_p^2 = 0.286$), indicating a significant decrease from pre-test to post-test ($p = 0.005$; Figure 11B). There were no significant effects or interaction for radial clearance for the trail foot ($p > 0.05$). For the lead foot placement, there was a significant main effect of Test for position before the obstacle ($F_{1,24} = 6.483$, $p = 0.018$, Wilks' $\Lambda = 0.787$, $\eta_p^2 = 0.213$), revealing a significant increase from pre-test to post-test ($p = 0.018$; Figure 11C). There were no significant effects or interaction for position after the obstacle for the lead foot ($p > 0.05$). For the trail foot, there was a significant main effect of Test for position before the obstacle ($F_{1,24} = 7.585$, $p = 0.011$, Wilks' $\Lambda = 0.760$, $\eta_p^2 = 0.240$), indicating a significant increase from pre-test to post-test ($p = 0.011$; Figure 11D). There were no significant effects or interaction for position after the obstacle for the trail foot ($p > 0.05$). For the lead foot stride length, there was a significant interaction ($F_{1,24} = 4.449$, $p = 0.046$, Wilks' $\Lambda = 0.844$, $\eta_p^2 = 0.156$), indicating an increase from pre-test to post-test within the YT group ($p = 0.004$; Figure 11E). For the trail foot stride length, a significant Interaction was also observed ($F_{1,24} = 7.653$, $p = 0.011$, Wilks' $\Lambda = 0.758$, $\eta_p^2 = 0.242$), revealing a significant increase from pre-test to post-test within the YT group ($p = 0.012$; Figure 11F).

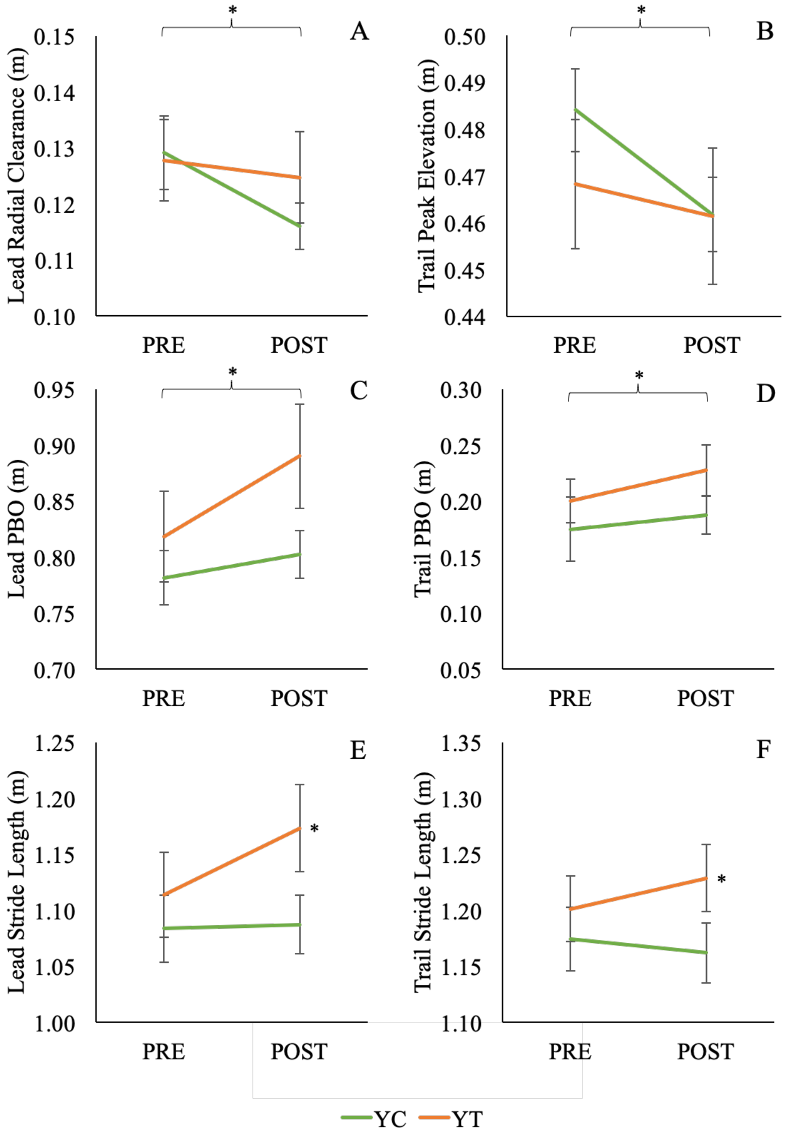

Figure 11. Significant Obstacle Crossing Metrics from Pre-test to Post-test for YC and YT. Variables include lead foot radial clearance (A), trail foot peak elevation (B), foot position before the obstacle (PBO) for Lead (C) and Trail foot (D), and stride length for Lead (E) and Trail foot (F). (*) = significant difference in Test.

Accwalker

For the Eyes Open condition, there was a significant interaction for stride time ($F_{1,24}$ = 15.288, p = 0.001, Wilks' Λ = 0.611, η_p^2 = 0.389), showing a decrease (i.e., better performance) from pre-test to post-test in the YT group ($p < 0.0001$) and that stride time at post-test was significantly decreased for YT compared to YC (p = 0.027; Figure 12A). There was also a significant main effect of Test for thigh ROM ($F_{1,24}$ = 7.108, p = 0.014, Wilks' Λ = 0.772, η_p^2 = 0.228), indicating a decrease from pre-test to post-test (p = 0.014; Figure 12B). There were no significant main effects or interaction for stride time CV, peak thigh flexion SD, or peak thigh return velocity SD ($p > 0.05$). For the Eyes Closed condition, there was a significant interaction for stride time ($F_{1,24}$ = 4.501, p = 0.044, Wilks' Λ = 0.842, η_p^2 = 0.158), indicating a significant decrease from pre-test to post-test in the YC group (p = 0.044; Figure 12C). There were no significant main effects or interaction for stride time CV, thigh ROM, peak thigh flexion SD, or peak thigh return velocity SD ($p > 0.05$). For the Head Shake condition, there were no significant main effects or interaction for any metrics: stride time, stride time CV, thigh ROM, peak thigh flexion SD, or peak thigh return velocity SD ($p > 0.05$).

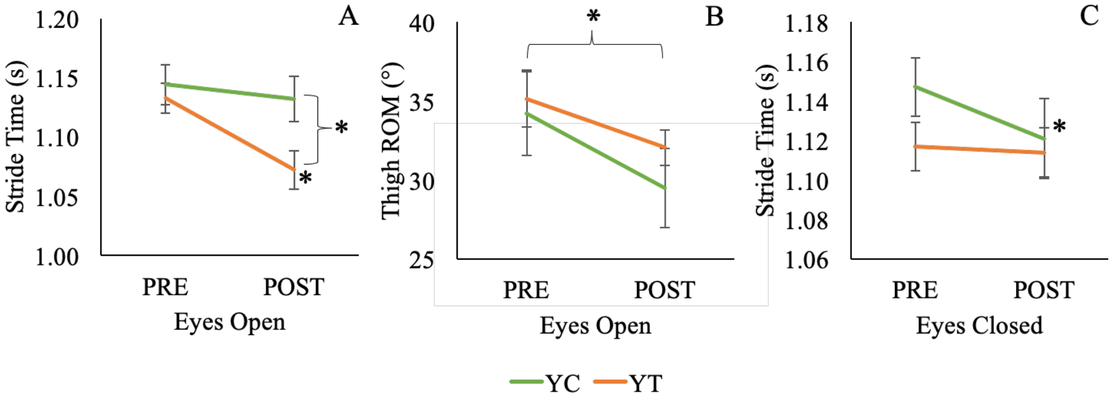

Figure 12. Significant AccWalker Metrics from Pre-test to Post-test for YC and YT. Variables are Stride Time – Eyes Open (A), Thigh ROM – Eyes Open (B), and Stride Time – Eyes Closed (C). (*) = significant difference in Test, (¥) = significant difference in Group.

Experiment 2

The aims of this experiment were two-fold: (Aim 4) to compare performance in VR over three weeks of training, and (Aim 5) to compare gait and balance with younger adults as a result of extended training duration. Our hypotheses for this second experiment were: (4) The younger adult training group would show improvements in performance within the VR environment in terms of decreased number of obstacles hit and decreased time to complete the course, and (5) The younger adult training group would show a further improvement in real-world gait and balance tests after three weeks of training from day 1 post-testing to day 9 post-testing.

Methods

Participants

Participants from the younger VR training group from Experiment 1 also participated in Experiment 2 (*N* = 10; 22.5 ± 2.7 years, 68.2 ± 11.0kg, 168.1 ± 10.3cm). Due to COVID-19 shutdown, 3 of the 13 from Experiment 1 started, but did not complete Experiment 2.

Experimental Design/Protocol

After participating in Experiment 1, participants returned for an additional 8 nonconsecutive days over 3 weeks. Experiment 1 served as day 1, days 2-8 consisted of VR training days, and day 9 consisted of a final VR training session and a secondary post-test (post-test-2). Days 2-8 were identical in protocol to the VR training on day 1. Participants came to the lab, were outfitted with the VR headset and foot trackers, and participated in 15 trials of the VR obstacle course with 30 seconds of rest in between each trial. Post-test-2 was identical to the day 1 post-test (post-test-1), consisting of a repeat of the 4 tasks: SRT, BBT, obstacle crossing, and AccWalker (Figure 13).

WEEK 1	Day 1 ***PRE-TEST*** ↳ 5 min of rest 15 VR Training Trials ↳ 5 min of rest ***POST-TEST-1***	Day 2 15 VR Training Trials	Day 3 15 VR Training Trials
WEEK 2	Day 4 15 VR Training Trials	Day 5 15 VR Training Trials	Day 6 15 VR Training Trials
WEEK 3	Day 7 15 VR Training Trials	Day 8 15 VR Training Trials	Day 9 15 VR Training Trials ↳ 5 min of rest ***POST-TEST-2***

Figure 13. Experimental Design of Experiment 2.

Statistical Analyses

In order to address hypothesis 4, the 9 training days were collapsed into 3 sets of 3 days to capture training duration: small (average of days 1-3), medium (average of days 4-6), and extended (average of days 7-9). Two separate repeated-measures (small, medium, extended duration) ANOVAs were calculated for the following: average time to complete the course and average number of yellow obstacle contacts. In order to address hypothesis 5, a series of repeated-measures (pre-test, post-test-1, post-test-2) ANOVAs were conducted for the four repeated tasks: SRT, BBT, Obstacle Crossing, and AccWalker. A Greenhouse-Geisser correction for the *F*-tests and follow-up pairwise comparisons with Bonferroni corrections were applied when applicable.

Results

Aim 4: Compare Performance in VR with Younger Adults over Three Weeks of Training

There was a significant main effect of Duration [*F*(1.114,10.022) = 7.979, *p* = 0.016, n_p^2 = 0.470], showing a decrease in time to complete the course from Small to Extended training duration (*p* = 0.015; Figure 14). A main effect of Duration was not observed for yellow obstacles (*p* > 0.05).

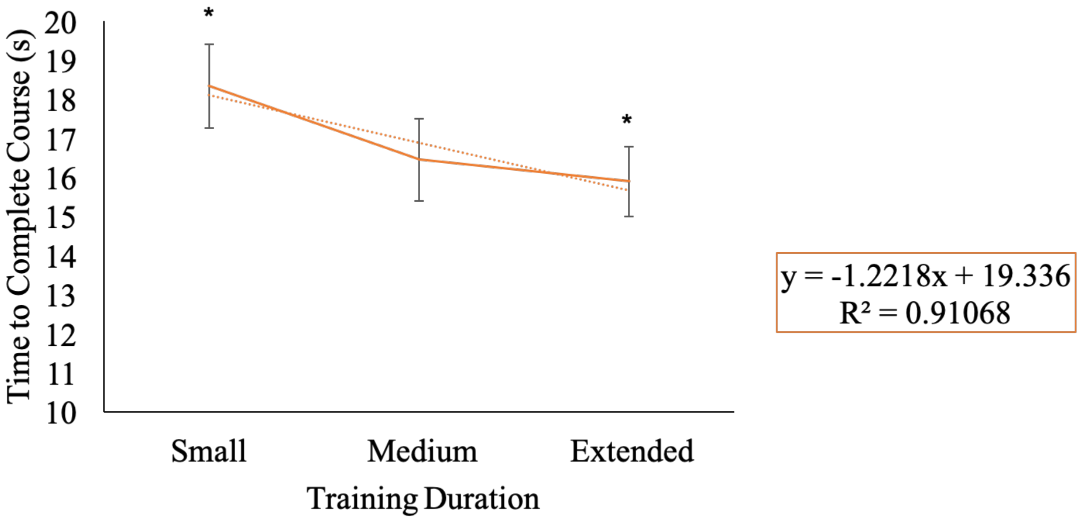

Figure 14. Time to Complete VR Course Over Training Duration. Small duration includes training days 1-3, Medium duration includes training days 4-6, and Extended duration includes training days 7-9. (*) indicates significant difference between training durations.

Aim 5: Compare Gait and Balance with Younger Adults as a Result of Extended Training Duration

SRT

There were no significant main effects of Test for SRT (*p* > 0.05).

BBT

For resultant velocity, there was a significant main effect of Test ($F_{2,18} = 3.984$, $p = 0.037$, $\eta_p^2 = 0.307$), showing an increase from pre-test (0.0011 ± 0.0006) to post-test-1 (0.0016 ± 0.0007, $p = 0.025$). Post-test-2 (0.0011 ± 0.0005) was not significantly different from pre-test or post-test-1 ($p > 0.05$).

Obstacle Crossing

There were no significant main effects of Test for any foot clearance metrics ($p > .05$). For the lead foot position, there was a significant main effect of Test for position before the obstacle ($F_{2,18} = 4.584$, $p = 0.025$, $\eta_p^2 = 0.337$), indicating an increase from pre-test (0.816 ± 0.162m) to post-test-1 (0.882 ± 0.185m, $p = 0.037$). Post-test-2 was (0.909 ± 0.176m) was not significantly different from pre-test or post-test-1 ($p > 0.05$). There was not a significant main effect for Test for position after the obstacle ($p > 0.05$). For trail foot position, there was not a significant main effect for Test for either position before the obstacle or position after the obstacle ($p > 0.05$). For the lead foot stride length, there was a significant main effect of Test observed for stride length ($F_{2,18} = 7.740$, $p = 0.004$, $n_p^2 = 0.462$), showing an increase from pre-test (1.111 ± 0.151m) to post-test-1 (1.175 ± 0.155m, $p = 0.015$) and a further increase from pre-test to post-test-2 (1.205 ± 0.143m, $p = 0.017$). For the trail foot, there was not a significant effect of Test for stride length ($p > 0.05$).

AccWalker

For the Eyes Open condition, there was a significant main effect of Test for stride time ($F_{2,18} = 7.328$, $p = 0.005$, $n_p^2 = 0.449$), indicating a decrease from pre-test (1.141 ± 0.048s) to post-test-1 (1.082 ± 0.060s, $p = 0.023$), and an increase from post-test-1 to post-test-2 (1.134 ± 0.41s, $p = 0.033$; Figure 15A). There was also a significant main effect of Test for stride time CV ($F_{2,18} = 5.121$, $p = 0.017$, $n_p^2 = 0.363$), driven by a decrease from pre-test (2.473 ± 0.219) to post-test-2 (2.167 ± 0.315, $p = 0.026$; Figure 15B). Post-test-1 was (2.456 ± 0.345) was not significantly different from pre-test or post-test-2 ($p > 0.05$). There were no significant main effects of thigh ROM, peak thigh flexion SD or peak thigh return velocity SD in the Eyes Open condition ($p > 0.05$). In the Eyes Closed condition, there was a significant main effect of Test for stride time CV ($F_{2,18} = 9.528$, $p = 0.002$, $n_p^2 = 0.514$), showing a decrease from post-test-1 (2.776 ± 0.472) to post-test-2 (2.278 ± 0.155, $p = 0.017$; Figure 15B). Pre-test (2.523 ± 0.324) was not significantly different from post-test-1 or post-test-2 ($p > 0.05$). There were no significant main effects of stride time, thigh ROM, peak thigh flexion SD or peak thigh return velocity SD in the Eyes Closed condition ($p > 0.05$). In the Head Shake condition, there were no significant main effects of any of the AccWalker variables ($p > 0.05$).

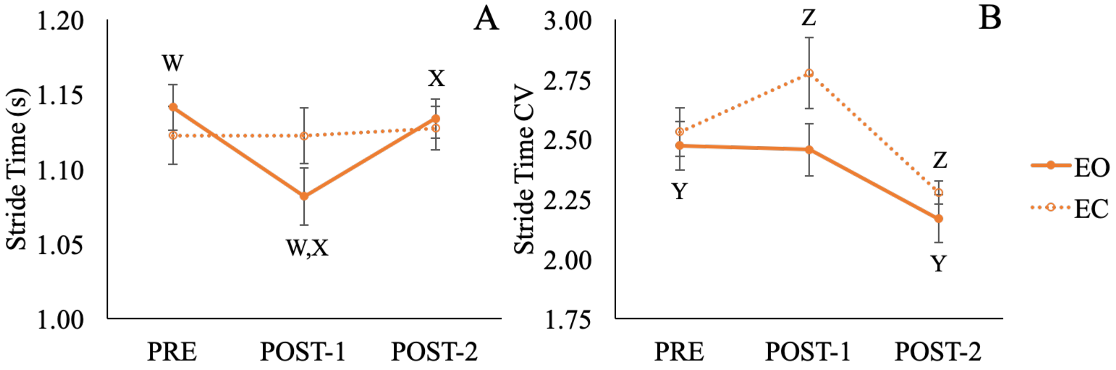

Figure 15. AccWalker Metrics Over 3 Weeks of VR Training. Stride time (A) and stride time CV (B) are shown for both the Eyes Open (EO) and Eyes Closed (EC) conditions. Same letters indicate significant differences between Tests for each condition.

Discussion

These experiments examined the performance of healthy younger and older adults within a novel VR obstacle course environment and the extent to which real-world gait and balance tests improve after engaging with the VR training. To address the Aims of our overall study, outcome measures from four related, yet separate areas were employed: (1) performance in the VR task (time to complete the course and number of obstacle contacts), (2) fundamental neuromotor ability (SRT), (3) static and dynamic balance tests (BBT and AccWalker, respectively), and (4) a functional gait test (obstacle crossing). Our results from both experiments are discussed in the context of these areas.

Examining performance within the VR obstacle course in Experiment 1, performance improved relative to time to complete the course. Across participants, time to complete the VR course significantly decreased as trials progressed, suggesting that learning occurred. We hypothesized that we would observe an age effect, with younger adults exhibiting a quicker completion time and a faster learning rate than older adults.

This hypothesis was partially supported, with the data showing that the older adults took longer to complete the course at all time-points. However, there was no age by training stage interaction, indicating that their learning rate was not different than the younger adults. These data support previous literature showing a parallel motor learning ability between older and younger adults (Ehsani et al., 2015; Mickeviciene et al., 2019; Voelcker-Rehage, 2008). In addition to a speed component in the VR performance assessment, we also included an accuracy component by asking participants to avoid yellow obstacles while completing the course as quickly and accurately as possible. There were no improvements in obstacle avoidance throughout the training stages by either group. It should be noted that both groups contacted very few obstacles in general (average 0.43 and 0.13 contacts with the 11 obstacles per trial in the older and younger groups, respectively), suggesting a floor effect and a lack of sufficient difficulty in the obstacle avoidance portion of the VR course. These data support the idea Voelcker-Rehage, (2008) suggested in their review paper that older adults can perform similarly to younger adults in low-complexity tasks. For Experiment 2, the younger adults continued to show a learning effect throughout the extended training, with a significantly quicker time to complete the course at the end of the last block of the nine days of training relative to the first block. These data are congruent with the younger adult motor learning rate reported by Coats et al. (2013). Their data show a gradual flattening of the learning rate after multiple days of practice (Coats et al., 2013), which was also observed acutely within day one (Figure 6A) and across the nine days (Figure 14).

To index fundamental motor ability, SRT was used. SRT has a long history of being used in this context (Clarkson, 1978; Lajoie & Gallagher, 2004; Lord et al., 1999; Luchies et al., 2002), and it generally shows that older adults have a slower SRT relative to younger adults (Clarkson, 1978; Der & Deary, 2006; Gottsdanker, 1982; Luchies et al., 2002; Myerson et al., 2007; Pierson & Montoye, 1958). However, Ehsani et al. (2015) showed in a serial reaction time test that older adults can exhibit a similar reduction of reaction time with practice relative to younger adults. Experiment 1 showed a reduction (medium effect size) in SRT in the younger adults after a single session of VR obstacle course training, whereas there was increase (small effect size) in the older adults SRT. This was contrary to our hypothesis that older adults would show a larger improvement relative to younger adults. It should be noted that the younger adult control group also exhibited a decrease in SRT in the post-test, indicating a practice effect. This practice effect likely influenced the SRT of the younger adult training group, but did not appear to be present in the older adult training group. In Experiment 2, there were no improvements in SRT observed in the younger adult group who continued the VR obstacle course training for nine days. Collectively, the data suggest that performing the VR training led to an acute change in SRT, but further improvements were not observed after more practice.

Decrements in balance are a known risk factor for falling. This study examined both static (BBT) and dynamic (AccWalker) balance. Traditionally, static balance has been assessed via examining in postural sway from the movement characteristics of CoP. Larger displacements and rate of movement have been associated with more postural sway in older adults (Berg, Wood-Dauphinee, et al., 1992; Maki et al., 1994; Muir et al., 2013; Swanenburg et al., 2010). Analyses of variability have provided additional insight into postural sway and risk of falling. Specifically, Sample Entropy (SampEn) is a measure of the complexity of the underlying dynamics of a time-series pattern (Pincus, 1991; Richman & Moorman, 2000). A decrease in SampEn can be characterized as a loss of complexity and an increase in regularity of the time-series pattern (Pincus, 1991; Richman & Moorman, 2000), which can in turn indicate less adaptive responses (Lewis A Lipsitz & Goldberger, 1992). Contrary to our hypothesis that older adults would improve balance after VR training, Experiment 1 showed older adults significantly increased path length and a decrease in SampEn of the resultant velocity of CoP compared to younger adults, suggesting increased postural sway, and a reduction of complexity and adaptive response. It is plausible that the older adults may have experienced some fatigue due to the number of tasks completed in this study. Previous research has shown fatigue significantly increases path length within the BBT after a fatigue protocol with healthy young adults (Benedict et al., 2017). However, it should be noted that the average path length of older adults in this study (21.3cm, post-test) is consistent with being in the 90th percentile of normative values for the 60-74 age populations (Goble & Baweja, 2018). In Experiment 2, our younger adult training group showed increases in resultant velocity from pre-test to post-test, but decreased back to pre-test levels after 3 weeks of extended training. This suggests a potential likelihood of acute fatigue due to completing the other tests more than an actual effect of training.

In our dynamic balance task, Experiment 1 showed the younger training group significantly decreased stride time in the Eyes Open condition from pre-test to post-test, suggesting that the decreased time to complete the VR course increased step rate which transferred to the AccWalker stepping-in-place task. This effect was not seen in the older adults and may indicate that older adults do not have the same flexibility in neuromotor control to transfer step rate learned in VR to a slightly different real-world task. The younger control group decreased stride time as well, although not significant. This observation for the control group may simply indicate a practice effect of repeated stepping in place that has previously been seen in healthy young adults (Kuznetsov et al., 2018). Both younger adult groups also decreased thigh ROM, suggesting that they were not lifting their leg as high, which may be a strategy of increasing step rate. With reference to stride time CV, older adults exhibited a more elevated stride time CV than the younger adults across all three conditions with a decreasing trend observed in the Eyes Closed (negative small effect size) and Head Shake (negative large effect size) condition, opposite from observed values with the younger adults (positive large and small effect sizes, respectively). This suggests that in general older adults have a higher stepping variability compared to younger adults which supports previous research that showed stride time CV increases with aging and after the onset of disease, such as Huntington's or Parkinson's (Hausdorff et al., 1998). However, with training, both groups converged to a somewhat similar CV. This may speak to a potentially optimal zone of CV for this task. In Experiment 2, the younger training group stride time increased back to pre-test levels after extended training within the VR environment. The reason for these responses are unclear, but will be examined in future training studies. Despite trends of initial increases in stride time CV seen in the younger adult training group, stride time CV significantly decreased after 3 weeks for training from pre-test for Eyes Open condition, and from post-test-1 for the Eyes Closed condition. Again, these responses are unclear, but will be examined in future studies.

Obstacle crossing is a functional gait task that is crucial for safely navigating our environment, and provides clues for how an individual may respond and adapt to challenging walking environments. Two main areas of analysis for obstacle crossing lies in examining foot clearance over the obstacle and foot placement before and after the obstacle. In regards to foot clearance, Experiment 1 showed the older adult training group generally exhibited a higher trail foot clearance than the younger adult training group. This is contrary to what has been previously reported. Previous research has established that older adults tend to have smaller foot trajectories and lower foot clearance (Chen et al., 1991, 1994; Muir et al., 2015). This may be a result of the relatively healthy older adult population that was recruited due to our restrictive inclusion criteria. In addition, there were not changes from pre-test to post-test. This is contrary to our hypothesis that was based on results from our previous study that utilizing non-immersive VR training on a treadmill showed increased foot clearance values after training (LoJacono et al., 2018). The results of the current study indicate that either the older adults either already exhibited an optimal clearance or that the environment may not have been challenging enough in order to potentially induce a change. One reason may be that the VR obstacles were the same height as the real obstacle, as in our previous research; however, participants were markedly better at avoiding obstacles in this study compared to our previous study, suggesting that our previous study proved more challenging and thus elicited a larger response in the real-world. Examining the younger adults, both training and control groups significantly decreased the distance between their foot and the obstacle (radial clearance) for the lead foot, as well as significantly decreased overall elevation (peak elevation) for the trail foot. This is contrary to our hypothesized increases due to training and also the results from our previous research (LoJacono et al., 2018). This could be a result of the larger quantity of obstacles that were meant to be avoided in this experiment compared to our previous research (105 versus 25, respectively). Foot clearance has shown to decrease during subsequent crossings of the same obstacle (Rhea et al., 2010) until eventual obstacle contact is made (Heijnen et al., 2012). Additionally, the lead and the trail foot showed decreases in different, yet related, obstacle crossing metrics. The differences in these metrics between the lead and trail limbs further support the suggestions of previous research that the lead and trail limbs function independently from one another (Heijnen et al., 2012; Mohagheghi et al., 2004; Patla, 1998; Patla et al., 1996; Rietdyk & Rhea, 2011), allowing each to individually modulate itself as needed. Experiment 2 showed no effects of extended training duration on foot clearance, again suggesting the obstacle course may not have been challenging enough to illicit a real-world response.

In Experiment 1, younger and older adults both similarly improved the lead foot's position before obstacle. Position before the obstacle increased, indicating an earlier initiation of crossing the obstacle. Earlier initiation of crossing allows for more time to adapt foot trajectory before crossing (Patla, 1998), ensuring a more proper placement of the foot at completion of crossing, and decreasing the risk of obstacle contact. Proper foot placement is crucial for the lead foot as after crossing it become the stance foot, bearing most of the weight of the body and aptly controlling the center of mass. Thus, if the obstacle is contacted by the trail foot when it is further forward in swing phase, it will provide a lesser destabilizing moment to challenge the center of mass, keeping it more stable and at lesser risk of tripping and subsequently falling (Chen et al., 1991). However, in this study, the trail foot also increased its position before the obstacle, allowing additional time of the trail foot to adapt its trajectory as well. This allows for more careful modulation of obstacle clearance to optimize crossing and decrease risk of obstacle contact (Chou & Draganich, 1998). Lead stride length also increased which may be a function of increased position before the obstacle and relatively steady position after the obstacle. As these improvements were seen overall, it appears there is not a differential effect of training; however, stride length significantly increased for the younger training group for both the lead and trail limb, suggesting potential changes in foot trajectory shape. Differences in foot trajectory have been seen with older and younger adults (Muir et al., 2015), so it is likely that a deeper analysis of foot trajectory may provide more insight into these changes. Future studies should examine additional cross metrics of foot trajectory over an obstacle to understand the effect of training on obstacle crossing trajectory strategies. Lastly, in Experiment 2, extended training in the younger adults showed an increase in the lead foot’s stride length and a trending increase in position before the obstacle. This suggests that extended training in a VR course may further improve obstacle crossing strategies.

A few limitations are present in this study. First, there was not an older adult control group for comparison to the older training group. As such, it is difficult to ascertain if differences with regards to the older adult training group are due to age, to training, or a potentially a combination of both. Second, in order to ensure participants could feasibly complete our VR obstacle course in a safe manner, our inclusion criteria were very restrictive. Our hypothesized improvements due to training and the extent to which responses were expected to be elicited were not always observed. This may be a result of our participants whom were in good health and relatively high functioning, potentially as a function of the restrictive inclusion criteria. Third, although participants improved in VR in terms of time to complete the course, participants were relatively accurate in completing the course, suggesting a potential lack of difficulty within the course. Difficulty could be increased by including a progression through varying levels of our VR obstacle course, in terms of height, number, and types of obstacles. Implementing dynamically moving obstacles may also increase difficulty. Warren and colleagues have used stationary and moving targets and objects to modify walking trajectory (Warren & Fajen, 2008), providing a potential way to scale difficulty. Lastly, a blocked practice schedule was utilized for learning within the VR course with participants executing the same sequence of obstacles every trial. A blocked schedule has been shown to enhance skill acquisition, however, a randomized trial structure has been shown to enhance the retention and transfer of learned skills compared with a blocked trial schedule (Shea &

Morgan, 1979). Future studies should determine the effect of varying levels of difficulty with the VR course, dynamically moving obstacles, and variable practice schedules, and analyze the subsequent effects on learning and real-world gait and balance. Lastly, all statistical comparisons utilized Bonferroni corrections in follow-up post-hoc tests. Bonferroni corrections were chosen due to small sample sizes and wanting to err on the side of caution. A study design with a larger sample size could potentially use a more sensitive post-hoc test to determine more specific results.

In conclusion, this study examined the effect of a novel VR obstacle course on real-world gait and balance tests in younger and older adults. Although, age-related differences were observed, older and younger adults showed improvement in performing the VR course and transferred these improvements to some of the tests of neuromotor control in the real-world. Future studies should be designed to further examine these responses in older adults after extended training, and make comparisons to an age-related control group.

CHAPTER V

EVALUATING THE USE OF PATIENT-REPORTS AND CLINCIAL MEASURES TO PREDICT PERFORMANCE WITHIN A DYNAMIC VIRTUAL REALITY OBSTACLE COURSE ENVIRONMENT

Introduction

Falling in older adults is a major public health concern (Handelsman, 2011). In the U.S. during 2014, 2.8 million older adults aged 65 year and older sought emergency treatment for a fall-related injury, over 800,000 were consequently hospitalized, and 27,000 died – all as a result of a fall (Bergen et al., 2016). In addition, injuries from falling decrease physical capacity (Rubenstein, 2006; Tinetti et al., 1988), leading to a decreased capability to independently live without assistance from a family member or caretaker (Kuzuya et al., 2006; Sattin et al., 1990). Furthermore, older adults also suffer mental consequences as a result of a fall. Older adults who have fallen exhibit an increased fear of falling – resulting in a lack confidence in completing activities of daily living, poorer balance and lower-extremity functional mobility, and an overall decrease in quality of life (Cumming et al., 2000; King & Tinetti, 1995; Landers et al., 2016; Li et al., 2003; Maki et al., 1991; Vellas et al., 1997).

Decrements in gait and balance control are tied to increased risk of falling in older adults. A variety of clinical assessments exist to quantify the extent to which an older adult may have a decrement in gait and/or balance and therefore at risk of falling. Some of these clinical assessments include the Functional Gait Assessment (FGA), Berg

Balance Scale (BBS), and Simple Reaction Time (SRT) test. The FGA asks participants to perform 10 different gait challenging tasks: walk at normal, fast, and slow speeds, while vertically and horizontally turning their head, over an obstacle, in tandem, ending about face, straight with eyes closed, backwards with eyes open, and while ascending and descending stairs (Wrisley et al., 2004). A cutoff score of 22 has shown to be effective in classifying fall risk in older adults and predicting unexplained falls in community-dwelling older adults (Wrisley & Kumar, 2010). The BBS examines performance in tasks that are related to balance and common in everyday life (Berg, 1989). Specifically, question 14 of the BBS asks participants to stand on one leg for up to 10 seconds and has been shown as a significant predictor in determining fall risk in older adults (Lajoie & Gallagher, 2004). Reaction time is defined as time between the onset of a visual stimulus to completion of the execution of a movement response; and more specifically, simple reaction time includes one response to one unexpected stimulus (Schmidt & Wrisberg, 2008). SRT increases as older adults further age (Clarkson, 1978; Gottsdanker, 1982; Pierson & Montoye, 1958), and has been associated with decreased lateral stability (Lord et al., 1999), and increased risk of falling (Lajoie & Gallagher, 2004).

Fall risk in older adults is also tied to self-perception of health and well-being. Patient-reports are valid indicators of capabilities and actual fall risk (Cumming et al., 2000; Lajoie & Gallagher, 2004). Commonly utilized patient-reports are the Medical Outcomes Study 36-item Short Form health survey (SF-36) and the Activities of Balance Confidence (ABC) scale. Low SF-36 scores are associated with low fall-related self-efficacy, and those with a low-fall-related self-efficacy exhibit an increased risk of falling, reduced ability to complete activities of daily living, and an increased fear of falling (Cumming et al., 2000). Individuals with higher scores on the SF-36 are considered to be in a more favorable health state (Brazier et al., 1992). The ABC scale provides a measurement of confidence in completing balance-challenging activities of daily living. ABC scores are correlated with 3 physical function levels in older adults: (1) High functioning (> 80), typically seen in older adults who are physically active; (2) Moderate functioning (50-80), seen in those with chronic health problems or living in retirement centers; and (3) Low functioning (<50), i.e. those receiving home care (Myers et al., 1998). Lower scores on the ABC represent a lack of balance confidence and are associated with decreased physical functioning (Myers et al., 1998), balance-impairment (Cho, Scarpace, & Alexander, 2004), and fall risk (Lajoie & Gallagher, 2004; Landers et al., 2016)

Fall prevention programs have been designed to improve gait and balance, as well as self-perception of health and well-being, with some success. Emerging advancements in technology, such as virtual reality (VR), and accessibility to this technology may provide unique opportunities to provide motivational training in novel and individualized ways, leading to greater efficacy in, and adherence to, fall prevention programs. Training with VR has been shown to improve gait and balance (Jaffe et al., 2004; LoJacono et al., 2018; Mirelman et al., 2011, 2016a; Shema et al., 2014a). However, these studies have utilized non-immersive VR constrained to a treadmill, limiting natural movement. Immersive VR allows for training overground in all three directions that is more natural and similar to our everyday environments. This type of training requires a specific amount of confidence and general ability to adapt gait and maintain balance. As such, it is unknown who may benefit from training overground in a challenging overground VR environment. Patient-reports and clinical assessments that have been used to predict risk of falling via evaluation of physical functioning and capability may also be used to predict performance within an immersive overground VR environment. Predicting performance may allow clinicians to identify those who may be good candidates for VR obstacle course training interventions. The purpose of this study was to evaluate patient-reported surveys and clinical assessments as prerequisite measures for performance within an overground VR obstacle course environment. Our hypothesis was that ABC score, RAND-1 subscales, FGA score, simple reaction time, and BBS Q14 score would be significant predictors of performance within the VR obstacle course.

Methods

Participants

Twenty-one participants were enrolled in this study that included healthy young adults (N =13; 22.1 ± 2.5 years; 168.3 ± 8.6cm; 68.3 ± 10.8kg) and older adults (N = 8; 67.0 ± 4.4 years; 164.6 ± 5.9cm; 63.8 ± 11.4kg). Participants were free of any cognitive, vestibular, or neurological disorders, musculoskeletal injuries, and current pregnancies. They were able to walk for 15 minutes without the use of assistive devices, had normal or corrected-to-normal vision, and a Body Mass Index of < 30.

Experimental Procedures

All participants completed an online survey prior to coming to the lab that included a simple informed consent, a basic health history survey, questions about previous experience with video games and virtual reality, the Activities Specific Balance Confidence (ABC) Scale, and the Medical Outcomes Survey Short-Form 36 (SF-36). Upon arrival to the lab, participants completed a secondary consent form with all information about the laboratory portion of the study that included additional information on the variety of clinical walking and balance tests they would complete. Participants then completed the Functional Gait Assessment (FGA), Question 14 of the Berg Balance Scale (BBS), and a Simple Reaction Time (SRT) Test. After completing the clinical tests, participants rested for 5 minutes while seated before participating in the VR obstacle course.

The VR obstacle course was presented in a head mounted display – the Vive Pro (HTC, New Taipei City, Taiwan) – and created in the Unity Game Engine (Unity Technologies, San Francisco, CA, USA). Two Vive trackers (HTC, New Taipei City, Taiwan) were each placed on top of the participant's feet to allow a set of virtual sneakers to be mapped in real-time onto the participant's feet in VR to provide feedback of foot position with relation to the other objects in the virtual world. The VR obstacle course contained a set of yellow obstacles designed to be avoided (yellow bricks and vertical agility poles) and a set of blue obstacles designed to be stepped on (blue flat balance beam and steppingstones). Participants started in the black square and stepped over the yellow bricks, then wove around each of the yellow agility poles, proceeded to tandem walk across the blue balance beam, and finished with stepping on each of the blue stepping stones back to the black square (Figure 16). Participants were asked to complete the VR obstacle course as accurately as they can yet as quick as they feel comfortable. Feedback of performance within the VR course was provided via visual and auditory cues. If a yellow obstacle was contacted, it visually turned red and a negative error tone was played to the headset. If a blue obstacle was contacted, it visually turned green and a positive click sounds was played. After each trial, a summary popped up centrally in the visual field informing participants of the number of both yellow and blue obstacles that were contacted. Participants completed 15 trials with 30 seconds of rest in between. All procedures were approved by the University's Institutional Review Board.

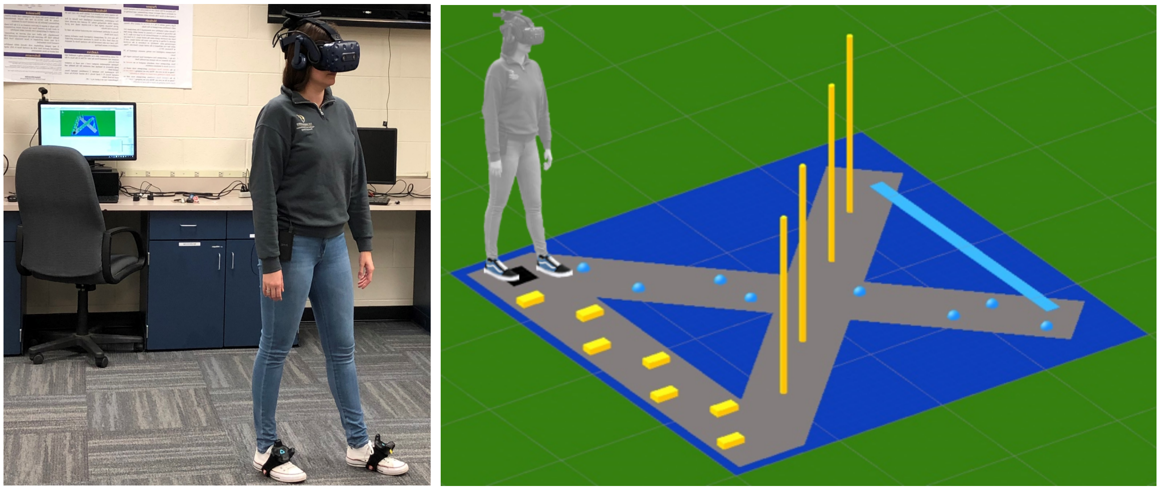

Figure 16. Depiction of VR Obstacle Course and Equipment Utilized to Portray Environment.

Outcome Measures

VR Obstacle Course Performance Metrics

Two variables were examined within the course: time to complete the course and number of yellow obstacle contacts. Time to complete the course was measured from the time the participant's first foot left the black square to the time both feet returned to the black square. Both variables were measured per trial and averaged across trials for statistical analyses.

Activities Specific Balance Confidence (ABC) Scale

The ABC is self-scored on a 10-point scale from 0% [not confident at all] to 100% [completely confident] (Myers et al., 1996; Powell & Myers, 1995). Participants were asked to rate their level of confidence in maintaining their balance while performing 16 different activities of daily living, such as walking around the house, up and down stairs, getting in and out of a car, etc. A summary ABC score was achieved by averaging the confidence level of all 16 activities.

RAND 36-item Health Survey 1.0 (RAND-1)

The RAND-1 is a survey based on the Medical Outcomes Survey 36 item Short-Form (SF-36). The SF-36 aims to measure both physical and mental aspects of an individual's quality of life (Ware Jr & Sherbourne, 1992). RAND-1 contains the same questions as the SF-36, but uses a simplified version of scoring on a scale of 0 [less favorable health state] to 100 [more favorable health state] (Hays et al., 1993). RAND-1 scores all questions and categorized the questions into 8 health scales: physical functioning, pain, role limitations due to physical health, general health, energy/fatigue, social functioning, emotional well-being, and role limitations due to emotional problems. All of these subscales have been shown to either contain no scoring differences in comparison with the SF-36 or be highly correlated (0.99) with SF-36 scores (Hays et al., 1993). For this study, only the scales of physical function, role limitations due to physical health, pain, general health, and energy/fatigue were assessed due to the physical nature of the task and aim to predict physical performance.

Functional Gait Assessment (FGA) Score

Each of the 10 tasks on the FGA is scored from 0 to 3, with higher scores indicating better functional gait. Scores were summed to create an overall score with a maximum value of 30. Overall FGA score was used for analysis in this study.

Berg Balance Scale Question 14 (BBS Q14) Score

Participants were asked to stand on one leg and were scored as: (4) able to lift leg independently and hold for > 10s; (3) able to lift leg independently and hold 5-10s; (2) able to lift leg independently and hold ≥ 3s; (1) tries to lift leg, unable to hold 3s, but remains standing independently; and (0) unable to try, needs assist to prevent fall. BBS Q14 score was analyzed for the dominant foot in this study, which was the answer to “if you were to kick a ball for distance, which foot would you choose to kick with?”

Simple Reaction Time (SRT) Test

In this study, participants completed a computerized SRT test. Participants were asked to observe a stoplight with an initial red light, and as soon as the stoplight turned green, to click the left button of the computer mouse. This was repeated for 5 trials and averaged together to form an average performance time for analysis.

Statistical Analyses

In order to predict performance in the VR obstacle course environment from patient-report surveys, two separate multiple regressions were calculated for each of the following: average time to complete the course, and average number of yellow obstacle contacts. The ABC score and RAND-1 subscale scores were entered as independent variables with age group (younger, older) as a covariate. In order to predict performance in the VR obstacle course environment from clinical tests, the FGA score, simple reaction time, and score for BBS Question 14 were entered as independent variables, with age group (younger, older) as a covariate, in separate multiple regression analyses (one for average time to complete the course, and average number of yellow obstacle contacts).

Results

Patient-reported Survey Measures of ABC Score and RAND-1 Subscales

A summary of all measures is listed in Table 6. A forward selection multiple regression model was calculated with time to complete course as the dependent variable and age group enter selected in block one to control for variance. ABC Score and RAND-1 subscales (physical function, role limitations due to physical health, energy/fatigue, pain, and general health) were included in block two and forward selected into the regression model with the entry point set at 0.05. Two separate regression models were identified (Table 7). The first regression model contained the first block of entry selected control variable of age group and was not significant, (R=0.410, Adjusted R^2 = 0.124, *F* $\text{Change}_{1,19}$ = 3.841, *p* change= 0.065). The second regression model included the second block of forward selected variables of ABC score and RAND-1 subscales and was significant. A significant amount of variance of time to complete the VR course can be explained by the RAND-1 pain subscale (R=0.648, Adjusted R^2 = 0.355, *F* $\text{Change}_{1,18}$ = 7.794, *p* change = 0.012) after controlling for age group. Participants' predicted time to complete the VR course is equal to 34.058 + 2.216(Group) - 0.220(SF-36 Pain), where Group is coded as 3=Younger and 4=Older. Follow-up partial correlations revealed a significant relationship between RAND-1 pain subscale and time to complete the VR course (*r* = -0.550, *p* = 0.012; Figure 17)

An additional forward selection multiple regression model was calculated with average number of yellow obstacle contacts as the dependent variable and age group enter selected in block one to control for variance. ABC Score and RAND-1 subscales (physical function, due to physical health, energy/fatigue, pain, and general health) were included in block two and forward selected into the regression model with the entry point set at 0.05. One regression model was identified (Table 7). The model contained the first block of entry selected control variable of age group and was not significant, (R=0.373, Adjusted R^2 = 0.094, *F* $\text{Change}_{1,19}$ = 3.075, *p* change = 0.096).

Table 6. Summary of Outcome Measures. All measures are represented as Mean(SD). *R1 = RAND-1 subscales; Role Physical = Role limitations due to physical health.*

Measure	***Overall***	***Younger***	***Older***
ABC Score	96.34 (2.88)	95.91 (3.17)	97.03 (2.36)
R1 Physical Function Scale	97.14 (6.44)	99.62 (1.39)	93.13 (9.23)
R1 Role Physical Scale	95.24 (12.79)	94.23 (14.98)	96.88 (8.84)
R1 Energy/Fatigue Scale	64.52 (17.24)	56.15 (15.57)	78.13 (9.61)
R1 Pain Scale	91.19 (10.57)	93.65 (10.14)	87.19 (10.64)
R1 General Health Scale	79.52 (10.60)	77.69 (9.27)	82.50 (12.54)
FGA Score	28.38 (1.50)	29.08 (1.32)	27.75 (1.04)
SRT (s)	0.323 (0.055)	0.307 (0.047)	0.350 (0.059)
BBS Q14 Score	3.81 (0.051)	4.00 (0.00)	3.50 (0.76)
Time to Complete Course (s)	21.50 (4.41)	20.11 (4.77)	23.75 (2.69)
Yellow Obstacle Contacts (#)	0.25 (0.39)	0.13 (0.24)	0.43 (0.52)

Table 7. Regression Model Summaries for Patient Reported Metrics

DV	**Model**	**IV**	**β**	***r***	***t***	***p***
Time to Complete Course	1	Age Group	3.638	0.410	1.960	0.065
	2	Age Group	2.216	0.298	1.325	0.202
		RAND-1 Pain	**-0.220**	**-0.550**	**-2.792**	**0.012**
Yellow Obstacle Contact	1	Age Group	0.293	0.373	1.754	0.096

**Bold variables indicate significance at $p < 0.05$. Both dependent variables (DV) and independent variables (IV) are shown.

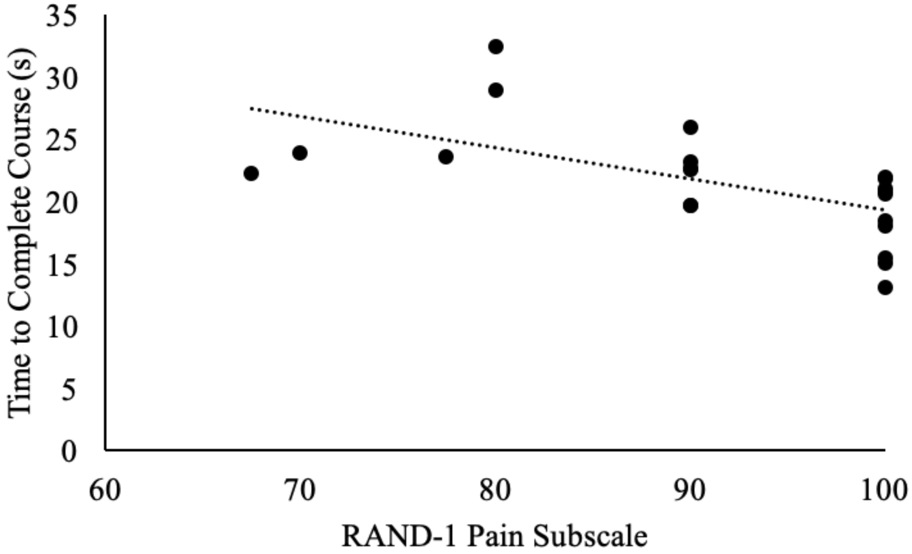

Figure 17. Relationship Between RAND-1 Pain Subscale and Time to Complete the VR Course

Clinical Assessment Measures of FGA, SRT, and BBS

A summary of all measures is listed in Table 6. A forward selection multiple regression model was calculated with time to complete course as the dependent variable and age group enter selected in block one to control for variance. FGA score, SRT, and BBS Q14 were included in block two and forward selected into the regression model with the entry point set at 0.05. Two separate regression models were identified (Table 8). The first regression model contained the first block of entry selected control variable of age group and was not significant, (R=0.410, Adjusted $R^2 = 0.124$, *F* $\text{Change}_{1,19} = 3.841$, *p* change= 0.065). The second regression model included the second block of forward selected variables of FGA, SRT, and BBS Q14 and was significant. A significant amount of variance of time to complete the VR course can be explained by SRT (R=0.676, Adjusted $R^2 = 0.397$, *F* $\text{Change}_{1,18} = 9.570$, *p* change = 0.006) after controlling for age group. Participants' predicted time to complete the VR course is equal to 0.963 + 1.610(Group) + 46.720(SRT), where Group is coded as 3=Younger and 4=Older and SRT is measured in seconds. Follow-up partial correlations revealed a significant relationship between SRT and time to complete the VR course ($r = 0.589$, $p = 0.006$; Figure 18).

An additional forward selection multiple regression model was calculated with average number of yellow obstacle contacts as the dependent variable and age group enter selected in block one to control for variance. FGA score, SRT, and BBS Q14 were included in block two and forward selected into the regression model with the entry point set at 0.05. Three regression models were identified (Table 8). The first regression model contained the first block of entry selected control variable of age group and was not significant, (R=0.373, Adjusted $R^2 = 0.094$, F $\text{Change}_{1,19} = 3.075$, p change = 0.096). The second regression model included the second block of forward selected variables of FGA, SRT, and BBS Q14 and was significant. A significant amount of variance of average number of yellow obstacle contacts can be explained by SRT (R=0.568, Adjusted $R^2 = 0.323$, F $\text{Change}_{1,18} = 4.882$, p change = 0.040) after controlling for age group. The third regression model was the strongest prediction model and showed a significant amount of variance can be explained by both SRT and BBS Q14 (R=0.720, Adjusted $R^2 = 0.519$, F $\text{Change}_{1,17} = 6.919$, p change = 0.018) after controlling for age group. Participants' predicted average yellow obstacle contact is equal to 2.195 + 0.275(Group) – 4.200(SRT) – 0.400(BBS Q14), where Group is coded as 3=Younger and 4=Older, SRT is measured in seconds, and BBS Q14 is scored from 0 to 4. Follow-up partial correlations revealed a significant relationship between average number of yellow obstacle contacts and SRT (*r* = -0.605, *p* = 0.006; Figure 19A), as well as BBS Q14 Score (*r* = -0.538, *p* = 0.018; Figure 19B).

Table 8. Regression Model Summaries for Clinical Assessments

DV	Model #	IVs	B	*r*	*t*	*p*
Time to Complete Course	1	Age Group	3.638	0.410	1.960	0.065
	2	Age Group	1.610	0.221	0.961	0.349
		SRT	**46.720**	**0.589**	**3.094**	**0.006**
Yellow Obstacle Contact	1	Age Group	0.293	0.373	1.754	0.096
	2	**Age Group**	**0.436**	**0.528**	**2.636**	**0.017**
		SRT	**-3.296**	**-0.462**	**-2.209**	**0.040**
	3	Age Group	0.275	0.394	1.765	0.095
		SRT	**-4.200**	**-0.605**	**-3.137**	**0.006**
		BBS Q14	**-0.400**	**-0.538**	**-2.630**	**0.018**

**Bold variables indicate significance at $p < 0.05$. Both dependent variables (DV) and independent variables (IV) are shown.

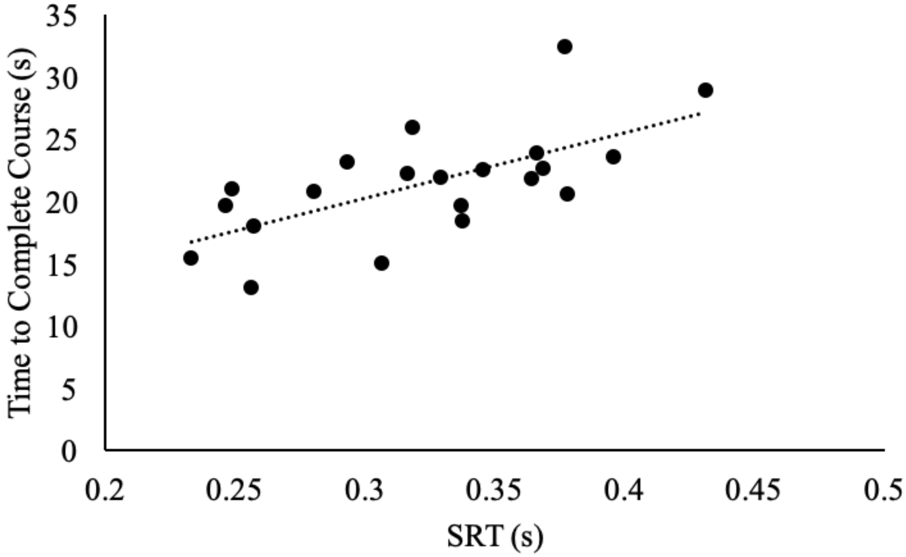

Figure 18. Relationship Between SRT and Time to Complete the VR Course

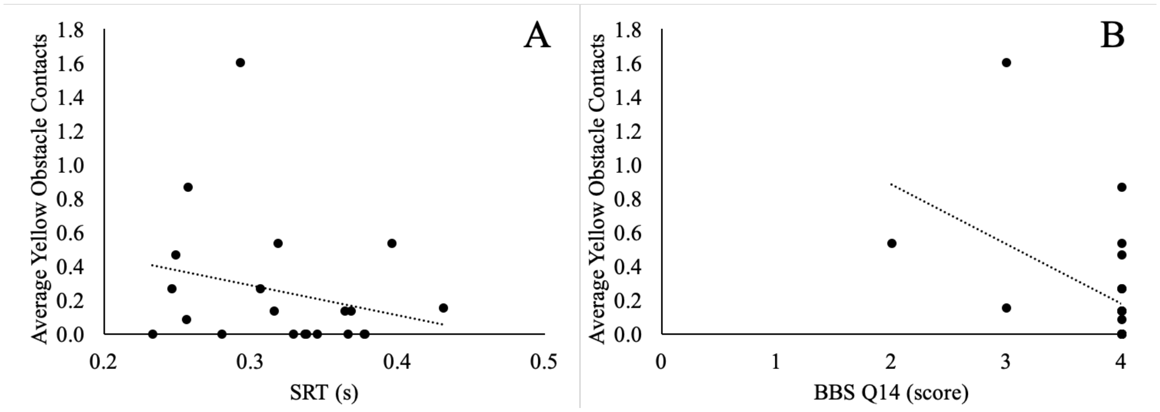

Figure 19. Relationship Between Average Yellow Obstacle Contacts and SRT (A) and BBS Q14 (B).

Discussion

This study examined outcomes from patient surveys (ABC and RAND-1) and clinical assessments (FGA, SRT, and BBS Q14) as potential predictors for performance within an overground VR obstacle course environment. Performance was assessed via time to complete the course and average number of obstacle contacts. We hypothesized that ABC score, RAND-1 subscales, FGA score, SRT, and BBS Q14 score would be significant predictors of performance within the VR obstacle course. Conversely, only RAND-1 Pain scale, SRT, and BBS Q14 score emerged as significant predictors of performance.

The RAND-1 Pain scale emerged as a significant predictor for time to complete the course. The scale indicates how much bodily pain has been experienced in the past 4 weeks and the extent to which this pain has interfered with normal work both inside and out of the home. Decreases indicate more pain and more interference everyday life as a result. Chronic pain has been associated with decreased physical activity and fear of movement in older adults (Larsson et al., 2016). It this study, our older adults reported less favorable pain levels on average than our younger adults (87.19 versus 93.95, respectively) and were slower in course completion (23.75 versus 20.11s, respectively). Thus, it seems congruent that an individual with more pain would be more cautious in placing physical stress on the body and slower to complete the course as a result.

Congruent with our hypothesis, SRT significantly predicted time to complete the course, as well as obstacle contact. SRT is a proxy for information-processing, as reaction time measures processing speed. As SRT increases, this indicates that the time taken to elicit a response is slower as information must be visually observed an interpreted, then an action plan must be created in the central nervous system, and finally executed by the peripheral nervous and muscular systems (Welford, 1988). Slower time to complete the VR course suggests that participants spent more time processing the information provided within the environment in order to complete it successfully without falling. Therefore, increased in SRT may be a predictor of time to complete the course as it indicates an individual's information processing speed. However, combining this finding with the association between increases in SRT and decreases in average number of obstacle contacts may reflect a speed accuracy trade-off, classically explained by Fitts (1954). A speed-accuracy trade-off has previously been found in a study examining running towards and stepping on targets (Bradshaw & Sparrow, 2000), thus the idea of a speed-accuracy trade-off within a VR obstacle course is plausible. Those who had an increased processing speed (as shown by a decreased SRT) completed the course faster, but also had more obstacle contacts and vice versa, regardless of age group. Future work could aim to understand this relationship in greater depth by emphasizing either speed or accuracy within the instructions.

BBS Q14 significantly predicted obstacle contact. BBS Q14 examines an individual's ability to control the body's center of mass within a small base of support. High scores indicate an increased ability to control the center of mass and thus balance. In this study, the results suggest those with lower scores were more apt to contact an obstacle. However, these results should be interpreted with caution. Of our 21 participants, only 3 scored less that the perfect score of 4. Thus, the utility of this metric in the context of predicting VR performance should be examined in future studies.

Contrary to our hypothesis, FGA and ABC scores were not significant predictors for performance within the VR obstacle course. This may be due to the high average scores of FGA and ABC observed in our participants. Younger and older adults scored on average 29.08 and 27.25, respectively, out of 30 on the FGA. In regards to the ABC, younger and older adults scored on average 95.91 and 97.03, respectively. Thus, regardless of age, our participants scored very highly on these measurements and it is plausible that these may be significant predictors of performance in more low-functioning individuals.

There are a few limitations in this study. First, it should be noted that conclusions based on predictions of obstacle contact should be mindful that the average number of obstacle contacts was very low for participants in this study. Average obstacle contact ranged from 0 to 1.6 of 11 possible contacts per trial with overall averages across subjects of 0.13 for young adults and 0.43 for older adults. Thus, it is unclear what predictors may emerge with a more challenging VR obstacle course. Second, our inclusion criteria were relatively restricted to high-functioning individuals. As such, more participants with lower scores on patient-reports and clinical tests are needed to have a more robust interpretation of the extent to which these assessments may predict performance with in the VR environment.

In conclusion, pain (RAND-1 pain subscale), reaction time (SRT), and one-legged stance balance (BBS Q14) may be significant predictors of performance within an overground VR obstacle course environment in terms of time to complete the course and average rate of obstacle contact. However, future work should examine these predictors in those with lower values in the clinical assessment discussed in this study to further understand these metrics as potential prerequisite measures for participation in an overground VR obstacle course.

CHAPTER VI

DISCUSSION

The purpose of this dissertation was to examine a novel overground VR obstacle course environment and its effect on functional mobility. Previous research examining training with VR components has shown to be successful in improving gait and balance in a variety of populations including younger healthy adults, older adults with various pathologies, and those with amputations, post-stroke, and Parkinson's (Baram & Miller, 2006; Beltran et al., 2014; Cano Porras et al., 2018; K. Cho et al., 2012; Darter & Wilken, 2011; Fung et al., 2006; Gates, Dingwell, et al., 2012; Jaffe et al., 2004; Kalron et al., 2016; Lee et al., 2014; Liao et al., 2015; LoJacono et al., 2018; Mirelman et al., 2011, 2016; Shema et al., 2014; Sin & Lee, 2013; Young et al., 2012). However, these training mechanisms rely on other equipment such as treadmills, force plates, and motion capture, limiting translation to our natural environment. Specifically, training with a treadmill constrains movement to specific timing and mainly in the anteroposterior direction, dissimilar to the way we navigate our everyday environment. There are additional gaps in the literature, including a lack of normative data of how healthy older adults without pathology may respond to a novel overground VR environment. These gaps limit the potential for VR to be adopted as a rehabilitation or prevention tool. Once normative data is established, VR could then be extrapolated to specific populations and potentially tailored to individual needs. There is also a lack of data on the characteristics of learning within overground VR and how individuals without aging or pathology respond to subsequent training. These gaps may be attended to by: (1) examining the extent to which younger adults respond to overground VR training and sequentially affect real-world gait and balance, and the differential responses of healthy older adults without pathology, (2) the effect of extended training duration on performance within VR and real-world gait and balance, and (3) the extent to which patient-reports and clinical assessments may act as prerequisite measures and potentially identify candidates for this type of overground VR training.

In this dissertation, Manuscript I – Experiment 1 measured the performance of both healthy younger and older adults within a novel VR obstacle course environment and the extent to which real-world gait and balance tests improved as a result of a single bout of VR obstacle course training. Age-related differences were observed in performance within the VR, although both similarly improved. These improvements transferred to some of the gait and balance tests with improvements observed due to training, however there were some age-related differences in the direction of responses. Manuscript I – Experiment 2 examined the changes in performance of healthy younger adults over three weeks of VR obstacle course training and the effects of extended VR training duration on real-world gait and balance. Time taken to complete the VR course continued to decrease with extended training and some further improvements obstacle crossing strategies were observed. Manuscript II evaluated patient-reported surveys and clinical assessments as prerequisite measures for performance within an overground VR obstacle course environment, and included patient-reported ABC scale and RAND-1 36-

item health survey, as well as FGA, BBS Question 14, and SRT assessments. RAND-1 Pain subscale, SRT, and BBS Q14 significantly predicted performance in VR. RAND-1 pain and SRT significantly predicted time to complete the course, whereas obstacle contact was significantly predicted by SRT and BBS Q14.

A variety of limitations exist for this dissertation. First, the inclusion criteria for this study were designed to understand responses of healthy older adults without underlying cognitive, neurological, and/or physical disorders, as well as to ensure that participants could perform the task safely. However, minimal variation was observed in the assessments, thus restricting our ability to understand the extent to which our variables may change due to VR training and predict performance in VR, ultimately limiting the potential to identify appropriate candidates for VR obstacle course training. Future work should aim to revise inclusion criteria to be less restrictive, or potentially screen candidates for physical function level using clinical assessments. Along these lines, our study was conducted at UNCG, thus our participants were highly motivated to participate and confident in their physically ability to arrive on campus and in the laboratory. Future work should use a validated physical activity questionnaire in order to control for physical activity and function. Second, there was not an older adult control group for comparison to the older training group. As a result, it is difficult to ascertain if differences with regards to the older adult training group are due to age, to training, or a potentially a combination of both. Additionally, our older adults did not train for an extended duration. Therefore, it is unknown if improvements may be seen in real-world gait and balance after extended training that were otherwise not observed within a single bout of training, or if our contradicting results may be due to time spent repeating tasks at post-testing and total time spent participating. Lastly, although participants showed improvements in performance in VR, it is plausible there was a potential lack of difficulty within the VR environment as evidenced by the low average rate of obstacle contact.

Future work should revise inclusion criteria, include an older adult control group, and examine an extended training duration in older adults. Additionally, future work should aim to enhance difficulty of the environment to understand how performance in VR, as well as real-world gait and balance, may change with a more complex environment. Despite limitations, this study exhibits a promising outlook for future work in overground VR obstacle course training.

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APPENDIX A

ADDITIONAL FIGURES

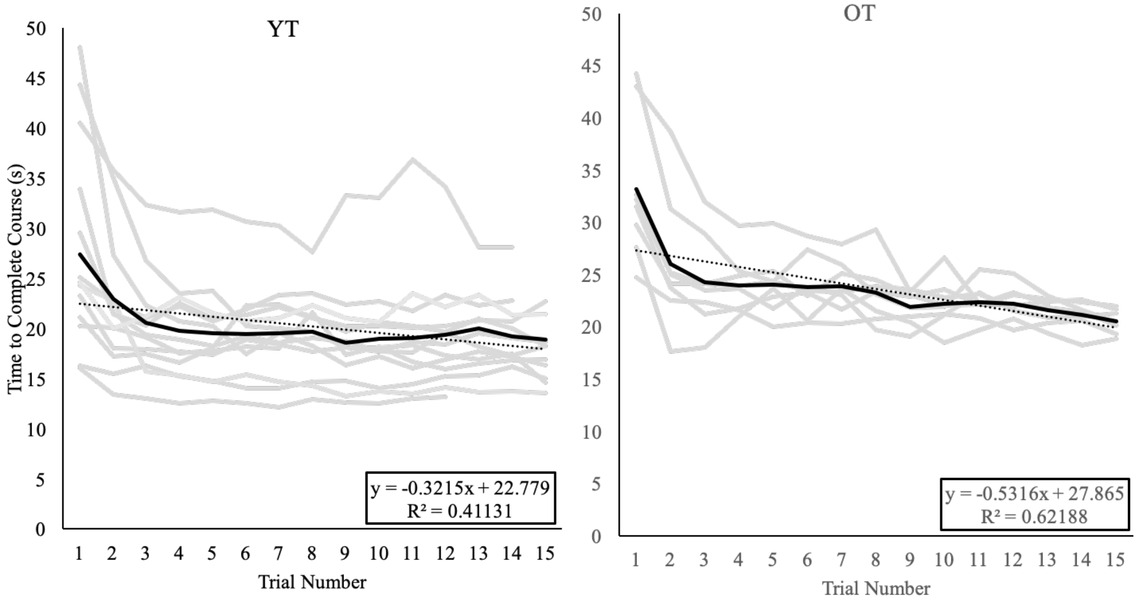

Figure A1. Time to Complete the VR Course for Each Subject in the Younger Training (YT) and Older Training (OT) Group. Grey solid lines represent individual subjects, black solid line represents the group average, and black dotted line represents the linear trend.