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A biomechanical approach to prevent falls in ergonomic settings

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2022

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Introduction: Fall-related injuries are exceptionally prevalent in occupational settings. While endangering the workers' health, falls cause poor productivity and increased economic burden in the workplace. Hence, identifying these threats and training workers to achieve proper postural control is crucial. **Purpose:** Study 1: To investigate the ankle joint kinematics in unexpected and expected trip responses during single-tasking (ST), dual-tasking (DT), and triple-tasking (TT), before and after a physically fatiguing exercise. Study 2: To investigate the impact of virtual heights, DT, and training on static postural stability and cognitive processing. **Methods:** Study 1: Twenty collegiate volunteers (10 males and females, one left leg dominant, age 20.35 ± 1.04 years, height 174.83 ± 9.03 cm, mass 73.88 ± 15.55 kg) were recruited. Ankle joint kinematics were recorded while treadmill walking during normal gait (NG), unexpected trip (UT), and expected trip (ET) perturbations with DT and physical fatigue. Study 2: Twenty-eight collegiate volunteers (14 males and females; all right leg dominant; age 20.48 ± 1.26 years; height 172.67 ±6.66 cm; mass 69.52 ± 13.78 kg; body mass index 23.32 ± 3.54 kg/m^2) were recruited. They were exposed to different virtual environments (VEs) over three days with and without DT.

Postural sway parameters, lower extremity muscle activity, heart rate, and subjective anxiety parameters were collected. **Results:** Study 1: Greater maximum ankle angles were observed during UT compared to NG, MDT compared to ST, and TT compared to ST, while greater minimum ankle angles were observed during ET compared to NG and during post-fatigue compared to pre-fatigue. Study 2: Greater postural decrements and poor cognitive processing were observed in high altitudes and DT. **Discussion & conclusions:** Study 1: Trip recovery responses are different between during DT, TT, and fatigue. Study 2: Static postural stability deteriorates at higher virtual altitudes and with DT, while it improves with a two-day training. Virtual height exposure reduces cognitive performance. **Importance:** The findings of these studies will provide insights into the biomechanics of falls in ergonomic settings and aid in designing functional and convenient fall prevention programs.

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CHAPTER I

INTRODUCTION

According to the Bureau of Labor Statistics (BLS), in the year 2019, 880 fatal occupational injuries occurred due to slips, trips, and falls (STFs), attributing to 16.5% of all occupational deaths. Among these, 711 deaths occurred due to a fall to a lower level (falling from a height), and the rest occurred due to falls on the same level (*Bureau of Labor Statistics (BLS)*, 2020; *National Census of Fatal Occupational Injuries*, 2020). The number of deaths due to STFs in 2019 was an 11% increase compared to 2018 (*National Census of Fatal Occupational Injuries*, 2020). Moreover, in the private industry sector, 244,000 non-fatal injuries occurred due to STFs, attributing to approximately 8.7% of all occupational injuries in 2019 (*BLS*, 2020). On average, the non-fatal injuries due to STFs caused 29.0 working days lost in the retail trade and 23.9 working days lost in the private industry in 2018 (*Employer-Reported Workplace Injuries and Illnesses*, 2019). STFs are frequently observed among the occupational categories such as construction workers, manufacturers, roofers, carpenters, tree trimmers, miners, and agricultural workers (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor*. 2017).

The outcome of the non-fatal injuries due to STFs vary in a wide range; such as but not limited to sprains, abrasions, contusions, lacerations, subluxations, dislocations, fractures, and head injuries (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor*. 2017). Depending on the nature of the injury, the impact varies from relatively minor, short-term effects to permanent disability. For instance, falling from a height could easily cause a spinal cord injury, leading to permanent disability. Thus, it is evident that STFs could affect the workers' health, quality of life, productivity, and earning capacity. These fall-related effects on workers decrease the productivity of the entire workplace, causing financial losses to the employer. Furthermore, medical bills, worker compensation, and hiring replacement workers increase the economic burden of the workplace. Annually, about $70 billion is allocated for occupational falls in the United States of America (*United States Department of Labor, BLS, Census of Fatal Occupational Injuries*, 2014). Hence, minimizing falls in the ergonomic setting benefits both the employee and the employer while improving the country's economy.

Postural stability and falls

Among the distinct causative factors of falls, loss of balance could be identified as a significant cause of slip and trip-related falls in ergonomic settings (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor*, 2017). Due to bipedal, erect stance, maintaining postural stability is a constant challenge for humans. Postural stability is defined as the ability to control the Center of Mass (COM) related to the Base of Support (BOS), while balance is defined as the ability to maintain the Center of Gravity (COG) within the BOS (Rodgers & Cavanagh, 1984; Winter, 1995). Balance is further divided into static and dynamic balance. In the conditions where the BOS is unchanging (e.g., quiet stance), the individual is said to maintain static balance, and in the instances when the BOS is changing (e.g., walking), the individual is said to maintain dynamic balance (Horak, 1987; Winter et al., 1998). Due to the similarity in definitions, the terms "balance" and "postural stability” are used synonymously in biomechanics. Therefore, those terms will be used interchangeably in this document as well.

Achieving and maintaining postural stability occurs via the afferent system, central nervous system (CNS), and the efferent system. (Horak, 1987; Horak, 2006; Shumway-Cook & Horak, 1986). The afferent system consists of three subsystems: visual, vestibular, and somatosensory systems, which gather information through the eyes, semicircular canals, and proprioceptors, respectively. Collected sensory information are sent to the CNS for integration, which eventually creates a motor plan for the required postural adjustments. This motor plan is executed via the efferent system, predominantly consisting of the nervous and musculoskeletal systems (Horak, 1987; Jacobs & Horak, 2007; Shumway-Cook & Horak, 1986). Thus, any factor that impacts the aforementioned systems could cause postural instability. The factors influencing postural stability are categorized as intrinsic (internal/human) and extrinsic (external/ environmental) factors. General health, age, vision, anatomy of the lower extremity, physical fitness, injuries, diseases, cognitive/motor fatigue, attention, experience, and anticipation are considered intrinsic factors (Horak, 1987; Horak, 2006; Kodithuwakku Arachchige et al., 2020; Kodithuwakku Arachchige et al., 2019). Nature of the supporting surface, task/s at hand, footwear, and environmental conditions (light, rain, snow) are considered extrinsic factors (Chander et al., 2014; Kodithuwakku Arachchige et al., 2020, 2021). When the intrinsic and extrinsic factors are not optimal, it could increase the amount of postural sway, which manifests as a loss of balance. Upon such induced instability, if the balance were not regained, it would eventually progress to a fall (Redfern & DiPasquale, 1997).

Effect of dual-tasking and fatigue on postural stability

Attention is considered a significant intrinsic factor that impacts postural stability (Abuin-Porras et al., 2018). Over the past years, dual-tasking (DT) has been used to assess attention and its effects on postural control. The simultaneous performance of two tasks is known as DT (Wickens, 1981). These tasks could be both motor (physical), cognitive (mental), or a combination of motor and cognitive tasks. In contrast to single-tasking (ST), DT requires attention switching between the two tasks; thus, the speed and accuracy of the performance are usually affected in DT (Lin et al., 2016). Performing a concurrent task while walking (e.g., carrying a load) is often observed among workers due to its associated benefits (e.g., achieving more tasks within a short time). Although gait was previously viewed as a semi-automatic process, it is currently considered a process that requires a significant allocation of attentional resources (Bloem et al., 2001). Therefore, an added secondary task during gait (i.e., DT) could hinder both activities due to divided attention. These performance decrements are further enhanced by other coexisting factors such as cognitive/motor fatigue, sleep deprivation, unexpected perturbations, environmental conditions, and injuries (Falbo et al., 2016; Granacher, Wolf, et al., 2010; Liu et al., 2017), which are common in the ergonomic settings.

Cognitive and physical fatigue is highly prevalent in occupational settings. Cognitive fatigue due to prolonged or exhausting mental tasks (Holding, 1983) is common among the professions as air traffic controllers, pilots, surgeons, and commercial vehicle drivers (Ćosić et al., 2019; Pan et al., 2021; Pimentel et al., 2019). Due to high work demands, long working hours, inadequate rest, and unfavorable environmental conditions, muscle fatigue is inevitable among the workers (Dong, 2005). Such undue muscle fatigue is frequently observed among occupational categories like firefighters, military personnel, and blue-collar workers (Dong, 2005). Moreover, muscle fatigue is known to cause significant decrements in static and dynamic postural stability (Kodithuwakku Arachchige et al., 2020; Kodithuwakku Arachchige et al., 2021). Such fatigue-induced postural instability decreases worker performance and increases the injury tendency (Dong, 2005). Hence, preventing undue muscle fatigue is crucial to minimize its negative effects on the workers.

Trips as a significant cause of ergonomic falls

Trips and trip-related falls are widely prevalent at workplaces due to the abundance of trip hazards like steps, rugs, cords, equipment, and tools (*BLS*, 2020). Furthermore, the tasks and environmental conditions in ergonomic settings, such as load carrying, poor lighting, and cluttered environments, increase the possibility of trips among the workers (Silver et al., 2016). Trips occur due to inefficient toe clearance during obstacle crossing or direct contact of the foot with an obstacle (Eng et al., 1994). Upon contacting a trip hazard, the individual's upper body undergoes a sudden forward (negative) moment, shifting the COG anteriorly. This forward moment, COG shift, and suddenly acquired unilateral stance significantly threaten the individual's balance control. The COG could even shift outside the BOS with larger perturbations, which must be promptly realigned back within the BOS to maintain balance. If this sudden temporary balance decrement is not corrected, the person will experience a fall. Balance recovery following a trip was formerly thought as a fully reflex-driven process. However, involvement of higher cortical structures with trip recovery is suggested, especially with repeated trip perturbations, providing evidence for motor learning (Jacobs & Horak, 2007). Lack of attention, divided attention, cognitive/motor fatigue, lack of anticipation, and inexperience are identified as causative factors of frequent trips and unsatisfactory trip recovery (Inkol et al., 2018; Paran et al., 2020; Weerdesteyn et al., 2003).

Effect of standing height on postural stability

Employments in the roofing industry, firefighting, construction, and manufacturing involve working at elevations. Working at an altitude is challenging in many ways, including postural instability, fear of heights, and anxiety. In addition, a fall to a lower level usually causes detrimental outcomes compared to a fall to the same level. While working at an altitude alone is highly challenging, the simultaneous job-related tasks such as walking on a sloped surface (roofers), working under unsatisfactory conditions (smoke/heat in firefighters), carrying objects (construction), and making numerous cognitive decisions make it more confronting. Thus, while working at a height, the employees must be extra vigilant, especially when it involves constant DT or multi-tasking. While being at a height, most individuals feel a fear of heights, which is natural to a certain extent. However, a significant proportion of society has a phobia of heights (acrophobia), even when not exposed to a considerable height. These individuals suffer fear, panic, and anxiety upon exposure to heights. At an altitude, fear develops due to the conflict between visual inputs and the perception of the absent boundaries, triggering an “unsafe” feeling (Huppert et al., 2012). Fear of falling itself cause limited motion, loss of balance, and falls (Huppert et al., 2020). Except for the fear, exposure to heights triggers other emotions, including anxiety and stress, increasing the sympathetic activity of the body, eventually affecting the worker’s performance (Cleworth et al., 2012; Fadeev et al., 2020; Kaur et al., 2019). Moreover, fear and anxiety are associated with reduced executive functions such as attention switching, resulting in ineffective DT. Therefore, the workers must be trained to counteract the fear of heights and height-related anxiety.

Thus, the purpose of this dissertation was to assess a few decisive biomechanical factors that could affect the maintenance of static and dynamic postural stability. The dissertation consists of two studies. The purpose of study one was to investigate the impact of DT, fatigue, and anticipation on trip recovery. The second study aimed to assess the DT, altitude, and training on static postural stability and cognitive processing. The results of these studies will provide insights into achieving better postural control, which ultimately contributes to minimizing falls in ergonomic settings.

Specific Aims and Hypotheses

Study 1

Specific Aim 1

To investigate the impact of DT, muscle fatigue, and anticipation on the trip incidence and trip severity.

H_{01}: The trip incidence and severity will not be affected by DT or muscle fatigue during unexpected and expected trips.

H_{A1}: The trip incidence and severity will be affected by DT or muscle fatigue during unexpected and expected trips.

Cognitive and motor DT increase the trip occurrence and severity due to the limited attention capacity of the human brain. This is manifested by the altered lower extremity joint kinematics (especially knee and ankle), toe clearance (TC), COM velocity, COM displacement, maximum trunk flexion, and lower extremity muscle activity. During walking, simultaneous cognitive or motor tasks cause divided attention, leading to a trade-off between the primary and the secondary tasks. Concurrent cognitive tasks, such as spatiotemporal assessments, identifying safety signs, and avoiding hazards are prevalent in ergonomic settings. Load carriage is a common secondary task observed in occupational settings. With the forward shifting of the COG during anterior load carriage, individuals tend to lean posteriorly to maintain balance. Further, carrying an anterior load obstructs the inferior visual field, increasing the possibility of trips. In addition, muscle fatigue affects the postural control system, contributing to poor postural stability while increasing the trip incidence. Moreover, the expected trip perturbations could be assumed to cause a lesser number of less severe trips than the unexpected trip perturbations. Therefore, the null hypothesis, “The trip incidence and severity will not be affected by DT or muscle fatigue during unexpected and expected trips" is expected to be rejected. It was hypothesized that the trip incidence and severity will be greater with DT and muscle fatigue during unexpected trips.

Specific Aim 2

To investigate the impact of DT, muscle fatigue, and anticipation on trip recovery.

H_{02}: The trip outcomes will not be affected by DT or muscle fatigue during unexpected and expected trips.

H_{A2}: The trip outcomes will be affected by DT or muscle fatigue during unexpected and expected trips.

DT and muscle fatigue carry the possibility of resulting in an unsuccessful trip recovery. The anticipation of a trip hazard may cause the individuals to adjust the muscle activation patterns and joint kinematics as a precaution to avoid or recover from a trip successfully. The impact of anticipation of a trip perturbation with DT and muscle fatigue has not been studied before. However, upon examining the related studies, better trip outcomes (fall rate, recovery step length, recovery step response time, and margin of safety) could be assumed with the expected trips than the unexpected trips. Therefore, the null hypothesis, "The trip outcomes will not be affected by DT or muscle fatigue during unexpected and expected trips" is expected to be rejected. It was hypothesized that the trip recovery will be less successful with DT and muscle fatigue during unexpected trips.

Study 2

Specific Aim 3

To investigate the impact of standing height, cognitive DT, and training on static postural stability.

H_{03}: Static postural stability will not be affected by different virtual environments, cognitive DT, or training.

H_{A3}: Static postural stability will be affected by different virtual environments, cognitive DT, and/ or training.

Maintaining postural stability requires cortical involvement; thus, performing a cognitive task during quiet stance can be considered DT. The divided attention between postural control and the cognitive task threatens the outcome of both tasks. Exposure to virtual heights elicits a negative impact on postural stability and exhibits an indirect relationship with increasing height. This resulted in postural instability and is associated with increased postural sway and altered lower extremity muscle activation patterns. Moreover, standing on a virtual edge (e.g., edge of a roof) increases the postural sway due to the individuals' anxiety caused by the perception of standing on an edge. Balance training with repeated exposure to virtual environments is known to improve balance and retention. Therefore, the null hypothesis "Static postural stability will not be affected by different virtual environments, cognitive DT, or training" is expected to be rejected. It was hypothesized that greater decrements to static postural stability will be observed with increasing virtual height, cognitive DT, and virtual edge. Also, it was hypothesized that these decrements will be improved with training and be retained after 48 hours.

Specific Aim 4

To investigate the impact of virtual reality-based training on cognitive processing.

H_{04}: Participants' cognitive processing will not be affected by virtual reality-based training.

H_{A4}: Participants' cognitive processing will be affected by virtual reality-based training.

Virtual reality-based training is shown to improve the performance of a given cognitive task. More specifically, hazard identification and management abilities are demonstrated to be improved upon training in immersive virtual environments. Faster hazard identification, identifying the previously ignored hazards, and identifying a higher number of hazards were reported upon virtual reality-based training. Thus, the null hypothesis "Participants' cognitive processing will not be affected by virtual reality-based training" is expected to be rejected. It was hypothesized that the participants' cognitive processing will be improved (identifying more hazards within a shorter duration) with training and retained after 48 hours.

Specific Aim 5

To investigate the impact of fear of heights on cognitive processing.

H_{05}: Participants' cognitive processing will not be affected by the exposure to different virtual heights.

H_{A5}: Participants' cognitive processing will be affected by the exposure to different virtual heights.

Fear of heights (acrophobia) and height-related anxiety are common conditions prevalent in more than 5% of the population. While some individuals are aware of their phobia, some manage to climb to an elevation but later develop anxiety after height exposure. This anxiety, fear, and stress increase sympathetic activity (sweating, tachycardia, hyperventilation, tremors) and increase the release of stress hormones such as cortisol. The human prefrontal cortex regulates a significant proportion of the brain's major executive functions (attention, task switching, response inhibition, working memory). However, the prefrontal cortex activity is shown to be affected by stress hormones, deteriorating executive functions of the brain. Such affected executive functions impair both postural control and cognitive processing. Therefore, the null hypothesis, "Participants' cognitive processing will not be affected by the exposure to different virtual heights," is expected to be rejected. It was hypothesized that the participants' cognitive processing ability will be decreased at virtual heights.

Operational Definitions

Center of Mass (COM)

The point at which all three mid-cardinal planes cross (Rodgers & Cavanagh, 1984). Around the COM, the body mass is uniformly balanced in the 3D (three dimensional) space (Winter, 1995)

Center of Gravity (COG)

The vertical projection of COM (Winter, 1995)

Center of Pressure (COP)

Once a body is in contact with the ground, the location where the sum of total pressures acting on a body that is in contact with the surface (Winter, 1995)

Posture

The orientation of the body segments within the space (Winter, 1995)

Balance

The ability to maintain the Center of Gravity (COG) within the Base of Support (BOS) (Winter, 1995)

Postural stability

The ability to maintain the Center of Mass (COM) within the BOS (Winter, 1995)

Postural orientation

Maintenance of proper relationship between body segments and postural tone (Horak, 2006)

Postural control

Maintenance of body posture in the space. This includes both postural stability and postural orientation (Horak, 1987; Horak, 2006)

Dual tasking

The simultaneous performance of two tasks (Wickens, 1981)

Muscle Fatigue

The inability to maintain the desired force production by a muscle (Enoka, 2015)

Executive Functions (EF)

The cognitive processes of the brain, which include response inhibition, working memory, and cognitive flexibility, are known as EF. These functions are regulated by the prefrontal and frontal areas of the brain (Diamond, 2013)

List of Abbreviations

COM- Center of Mass

COG- Center of Gravity

COP- Center of Pressure

BOS- Base of Support

GRF- Ground Reaction Force

MOS- Margin of Safety

TC- Toe Clearance

EMG- Electromyography

DT- Dual Tasking

VR- Virtual Reality

VE- Virtual Environment

CHAPTER II

LITERATURE REVIEW

The purpose of this chapter is to provide insight into the previous literature related to the biomechanics of static and dynamic postural stability. More specifically, scholarly articles on selected factors that could affect static and dynamic balance are analyzed and presented in nine sections as described below. The first section discusses the biomechanics of static and dynamic postural stability. The following two sections illustrate the biomechanics of trips and trip recovery. The fourth section presents the previous literature related to lower extremity muscle activity, while the fifth section is focused on the effects of muscle fatigue on trip biomechanics. The role of anticipation on trips is discussed in the sixth section, followed by a section on DT and trip biomechanics. The effect of standing height and VR-based training on static postural stability is then discussed, followed by the eighth section presenting the effect of acrophobia on postural stability and cognitive performance. Upon presenting the previous related work regarding DT on static postural stability and cognitive performance, the chapter ends with the conclusions drawn from the previous literature. The outline of this chapter is illustrated below.

- Biomechanics of static and dynamic postural stability
- Biomechanics of trips
- Biomechanics of trip recovery
- Lower extremity muscle activity and trips
- Lower extremity muscle fatigue and trips

- Role of anticipation on trips and trip recovery
- Dual tasking and trips
- Effect of standing height and VR-based training on static postural stability
- Effect of acrophobia on postural stability and cognitive performance
- Effect of dual-tasking on static postural stability and cognitive performance

Biomechanics of static and dynamic postural stability

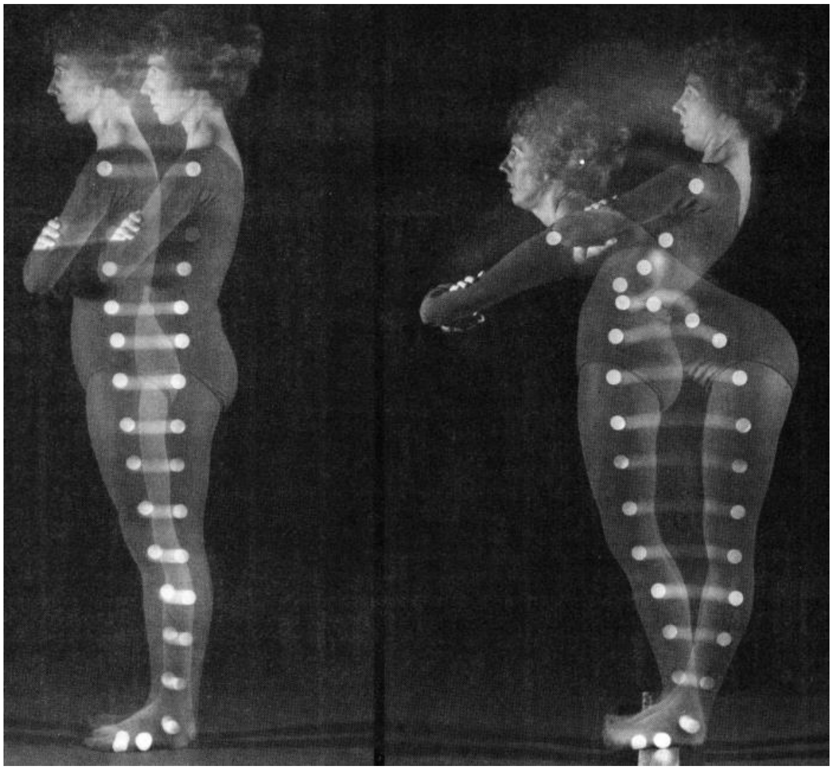
Maintaining postural stability is achieved through the visual, vestibular, neurological, and musculoskeletal systems (Anne Shumway-Cook & Horak, 1986). The visual system, which consists of both eyes, gathers information from the vicinity. The visual system is the fastest of the three sensory (afferent) systems and allows humans to react to sudden environmental changes (Winter, 1995). Poor vision due to improper lighting, obstruction of the visual field, or aging could affect the capabilities of this system leading to poor balance (Marigold & Patla, 2007). The vestibular system consists of the semicircular canals in the inner ear and is responsible for head position, head movements, and gaze maintenance during head movements. Although the vestibular system is the slowest sensory system, it provides reliable information, acting as a reference when the visual or somatosensory systems provide erroneous information (Winter, 1995). The vestibular system can be affected by ear infections, sudden inner-ear pressure differences, or head/body rotations (Renga, 2019). The proprioceptors, including muscle receptors (muscle spindles, Golgi tendon organs), joint receptors, and free nerve endings, make up the somatosensory system, which aids in determining the relative body position during different postures (Winter, 1995). This system can be affected by unstable support surfaces, improper footwear, or disorders like peripheral neuropathy (Kodithuwakku Arachchige et al., 2020).

The sensory information gathered from the three sensory systems are not simultaneously fed to the CNS, but the CNS retrieves information as required, known as the sensory organization (Enoka, 2015). For instance, in a well-lit room, on a firm surface, a healthy person will gather 70% of surrounding information from the somatosensory system, 20% from the vestibular system, and 10% from the visual system (Peterka, 2002). Furthermore, when one of these efferent systems is compromised, the other systems alleviate the loss; thus, the usual 70%, 20%, 10% ratio will not be preserved at all times (Peterka, 2002). The CNS integrates the received sensory information to determine the current body posture and create a motor plan with the required postural adjustments. The prefrontal cortex, motor cortex, cerebellum, thalamus, basal ganglia, brain stem, and many other supraspinal structures are involved in this process (Jacobs & Horak, 2007). This integration and planning that occurs in the CNS could be affected by neurological disorders, trauma, or any temporary condition that alters the executive functions of the brain (e.g., cognitive fatigue, stress, deception) (Arnsten, 2009; Peterson et al., 2018). The created motor plan is executed via the descending tracts that terminate in the spinal cord, sending efferent information to the muscles via lower motor neurons (Horak, 1987; Taube et al., 2006). Any condition that affects neural or muscular activity (e.g., muscle fatigue) could cause hindrances to the proper execution of the motor plan by the musculoskeletal system (Winter, 1995). Hence, multiple intrinsic and extrinsic factors act as internal and external perturbations to the postural control system, causing balance decrements. Once postural stability is affected, it is manifested as an increase in postural sway, which progresses to a fall if not corrected promptly (Taube et al., 2006).

Related to postural control, four main support strategies are described as ankle strategy, hip strategy, stepping strategy, and grasping strategy (Horak, 1987). In the ankle strategy, the person does not change their base of support; instead, they sway back and forth (anteroposterior sway) within their limits of stability (Horak, 1987). As the person keeps the feet fixed and sways about the ankle joint in the sagittal plane, they will paint an inverted cone in the space. More specifically, if the person's COM trajectory was tracked and joined to the feet at the beginning and end of the sway, it would be in the shape of an inverted cone. This is known as the inverted pendulum model in postural control (Horak, 1987; Horak, 2006; McIlroy & Maki, 1996). Thus, the body sways like an inverted pendulum when using the ankle strategy, allowing the individual to counteract smaller perturbations on a wide, firm surface (Horak, 2006). In hip strategy, following a perturbation, the individual creates a sudden moment around the hip, which lowers the COM and helps maintain COM within the BOS (Figure 1). The hip strategy is primarily used to counteract moderate perturbations while standing on a narrow surface (Horak, 2006). Grasping and stepping strategies are considered "change of support strategies" since the size of BOS changes during both strategies. In the stepping strategy, the individual takes a step forward to counteract perturbations, which widens their BOS and lowers the COM, improving postural stability. The stepping strategy occurs following larger perturbations when the COM can no longer be contained within the BOS without increasing the size of the BOS. In grasping strategy, the individual grasps an object (desk, chair) so that the BOS of the grasped object adds to the person's BOS, making the person more stable (Horak, 2006). From these strategies, the ankle strategy is mainly used by young adults, while the hip, stepping, and grasping strategies are commonly observed among the elderly (McIlroy & Maki, 1996).

Figure 1

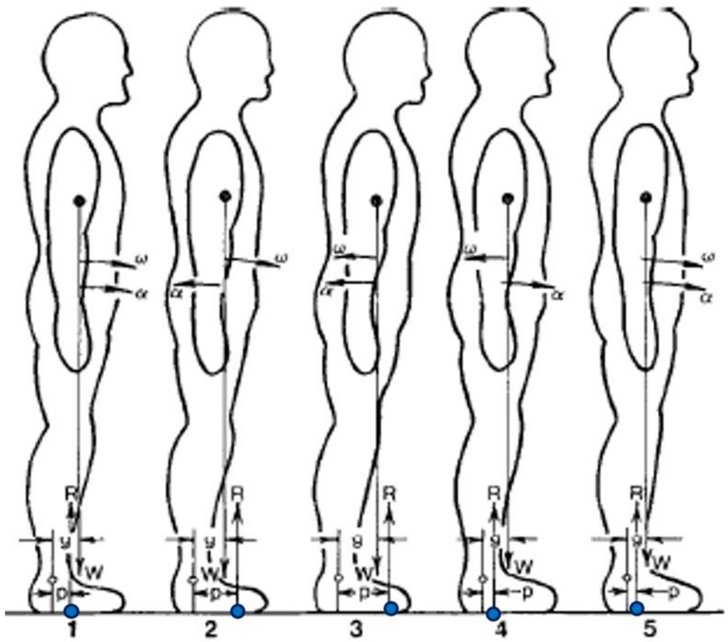
A demonstration of ankle strategy (left) and hip strategy (right) (Horak, 1987).



A person undergoes a certain amount of anteroposterior sway during quiet stance, known as postural sway. This postural sway occurs about the ankle joint due to the moments caused by gravity and body weight. During quiet bipedal stance, the weight of the body acts vertically towards the ground. As a result, an equal reactionary force (ground reaction force; GRF) acts in the opposite vertical direction towards the body. These are the only two major forces acting on the body during quiet bipedal stance. The bodyweight and GRF cause the lower extremity agonist and antagonist muscles to act about the ankle joint as a pulley system to maintain postural stability. When a person stands erect, these two forces are equal and act along parallel vertical lines, maintaining equilibrium. However, if there was a minimal forward lean, the moment arm for the bodyweight increases, creating a negative moment of the upper body, disrupting equilibrium (Figure 2). This negative moment causes an angular velocity and angular acceleration in the clockwise direction. At this point, the person sways towards the anterior, which must be immediately corrected to prevent a fall. The antigravity (postural) muscles (gastrocnemius, soleus, and erector spinae) concentrically contract to correct this forward lean, creating a positive moment (counterclockwise) of the upper body. As a result, the angular acceleration and angular velocity change towards the counterclockwise direction, causing a posterior sway of the person. Once the person is experiencing excessive posterior sway, postural muscle activity is ceased, reversing angular velocity and acceleration, which allows the body to get back to its original posture. Therefore, postural control is considered an equilibrium of angular moments about the ankle joint, which could be quantified using angular velocities and angular accelerations (Sasagawa et al., 2013; Winter, 2009).

Figure 2

Postural sway during quiet bipedal stance.



W: body weight; R: ground reaction force (GRF); p: moment arm for the GRF; g: moment arm for the bodyweight; ϖ: angular velocity, α: angular acceleration. Scenario 1: Quiet stance with no net moment; Scenario 2: Net negative upper body moment causing forward lean; Scenario 3: Antigravity muscles contract attempting to create a positive moment; Scenario 4: Net positive moment causing backward lean; Scenario 5: Achieving the original posture with zero net moment (Winter, 2009).

A force platform (force plate) is frequently used to quantify postural stability in laboratory settings. A force plate measures the degree of COP excursion, GRF, and moments. The force plate provides various sway variables, such as COP displacement in the AP and ML directions, sway velocity, sway area, 95% ellipsoid area, and sway length. Depending on the nature of each study, the appropriate sway variables could be selected and analyzed. COP excursions in the anteroposterior (AP) and medial-lateral (ML) directions are generally used to measure static postural stability. Higher values for these postural sway variables indicate greater balance decrements. Electromyography (EMG) is another commonly used laboratory equipment to assess postural stability and study the lower extremity muscles' contribution to postural control. EMG measures muscle activity, which is considered to be representative of muscle force production.

In the realm of biomechanics, postural stability is considered tow fold: static and dynamic. Since dynamic balance includes the continuous change of the BOS and an intermittent shift to the unilateral stance, maintaining dynamic balance is more challenging than static balance (Horak, 2006). Walking is an example of dynamic balance, and walking is considered a series of stepping strategies. As a person starts to walk (before taking a step forward), with the forward lean, their COG tends to shift outside of the BOS due to the resultant forward angular moment of the upper body. Therefore, the person must take a step forward in order to maintain balance. Thus, walking is seen as the person performing a series of stepping strategies.

The gait cycle is divided into stance and swing phases for education and clinical purposes. In the stance phase, the foot is in contact with the ground, while the foot is not in contact with the ground during the swing phase. The stance phase is further divided as heel strike, foot flat, mid stance, heel off, and toe-off, while the swing phase is divided as acceleration, mid-swing, and deceleration. Lower extremity muscles, including the tibialis anterior, gastrocnemius, soleus, quadriceps complex, and hamstrings complex, predominantly produce the force needed for propulsion (Levangie & Norkin, 2011). In gait biomechanics, gait patterns, muscle activity, joint kinematics, and spatiotemporal parameters are widely studied (Barbieri et al., 2014; Falbo et al., 2016). Gait velocity and cadence are considered temporal gait parameters, while step/stride length, step width, and foot angle are considered spatial parameters (Levangie & Norkin, 2011). Three-dimensional (3D) motion capture is widely used to assess gait in laboratory settings, especially to evaluate the joint kinematics and spatiotemporal parameters of the gait (Pijnappels et al., 2001), while EMG is commonly used to analyze the muscle activity (Barbieri et al., 2014).

Biomechanics of trips

Although the biomechanics of slips have been studied to a certain extent, there is still a dearth of literature on trip biomechanics. Some researchers have studied the biomechanics of obstacle clearance; however, obstacle clearance is more of a voluntary activity compared to tripping over an obstacle. Hence, the mechanics of obstacle clearance and trips are not completely comparable. In addition, the causation of the trip affects the trip recovery responses. For example, toe clearance (TC) is greater in obstacle-induced trips than in treadmill-induced trips (Troy & Grabiner, 2005). Moreover, many treadmill or platform-induced trips were caused when the participant was standing still (stance trips) (Inkol et al., 2018; Paran et al., 2020), while the obstacle-induced trips were caused when the subject was walking on the ground or treadmill (gait trips) (Patel & Bhatt, 2015; Wang et al., 2012). Thus, the recovery responses in these two situations are different, and the findings on the stance trips are not generalizable to gait trips. For instance, the time to initiate the recovery step was longer, and the recovery step length was shorter in stance trips on a treadmill compared to the gait trips using an obstacle to induce trips (Troy & Grabiner, 2005). Therefore, when studying trips and trip recovery biomechanics, extreme attention must be paid to the method of trip induction. Furthermore, up to date, the limited number of studies conducted on trips were mainly focused on the geriatric and clinical populations. However, trips, trip-induced falls, and trip-related injuries are highly prevalent in ergonomic settings. The majority of the employees in construction, manufacturing, and roofing are young, healthy adults (*Employed Persons by Detailed Industry and Age*, 2020). Therefore, more trip-related research is warranted among the young, healthy population that could be applied to the occupational population.

During a trip, the suddenly acquired forward angular moment of the upper body brings the subject's anterior surface towards the ground (forward loss of balance). Following tripping, the body undergoes a perturbation in all three dimensions, but the movements in the forward direction are more prominent (Burg et al., 2005). Other than the perturbation method, the severity of a trip depends on factors such as perturbation magnitude, nature of the walking surface, age, and general health (Silver et al., 2016; Smeesters et al., 2001; Wang et al., 2012). In the previous trip-related literature, distinct ways were used to induce a trip when the participants walk on the ground or treadmill. Obstacles (Schillings et al., 1996), ankle pulls (Karamanidis et al., 2011), and sudden treadmill belt velocity changes (Shimada et al., 2004) are some standard methods used to induce trips in laboratory settings. The lower limb that is used to take the immediate step after the trip (i.e., recovery step) is defined as the recovery limb, while the limb in the stance phase when tripping is known as the support limb (Pijnappels et al., 2004). Immediately after the positioning of the recovery limb, the support limb will move forward over the obstacle and be placed on the ground, which is known as the follow-up step (Eng et al., 1994; Pijnappels et al., 2004). In order to understand the severity of the trip, various parameters, such as TC, maximum trunk angle, maximum trunk angular velocity, recovery step length, follow-up step length, extrapolated COM (*X*COM) displacement, and forward COM velocity were used by the previous investigators (Bhatt et al., 2013; Bieryla et al., 2007; Okubo et al., 2018). The TC is considered the vertical distance from the ground to the crossing leg's toe during mid-swing (Winter, 1991). TC is determined by tracking the trajectory of the toe (Winter, 1991) and is used to determine the probability of tripping as well (Garman et al., 2015). Decreasing the mean/median TC or increasing the variability of TC indicates a greater probability of tripping (Begg et al., 2007). The maximum trunk angle is the angle between the vertical line and the trunk (midway between L3/L4 joint to shoulders) immediately after the recovery step (Bhatt et al., 2013; Eng et al., 1994). The recovery step length is considered the distance from the heel of the support limb to the heel of the recovery limb following the trip (Bhatt et al., 2013). Maximum trunk angular velocity is considered the trunk's velocity immediately after the recovery step (Bieryla et al., 2007). *X*COM is a calculated variability using the COM velocity in the sagittal plane, extrapolating that the COM trajectory is in the direction of COM velocity (Hof et al., 2005; Okubo et al., 2018). Thus, it is known as the velocity-corrected COM. The calculation is done based on the inverted pendulum model, using the equation,

$$X\text{COM} = (\text{position of the vertical projection of COM} + \text{COM velocity}) \times \sqrt{l/g}; \qquad (1)$$

where l refers to the leg length

g refers to the acceleration due to gravity (Hof et al., 2005).

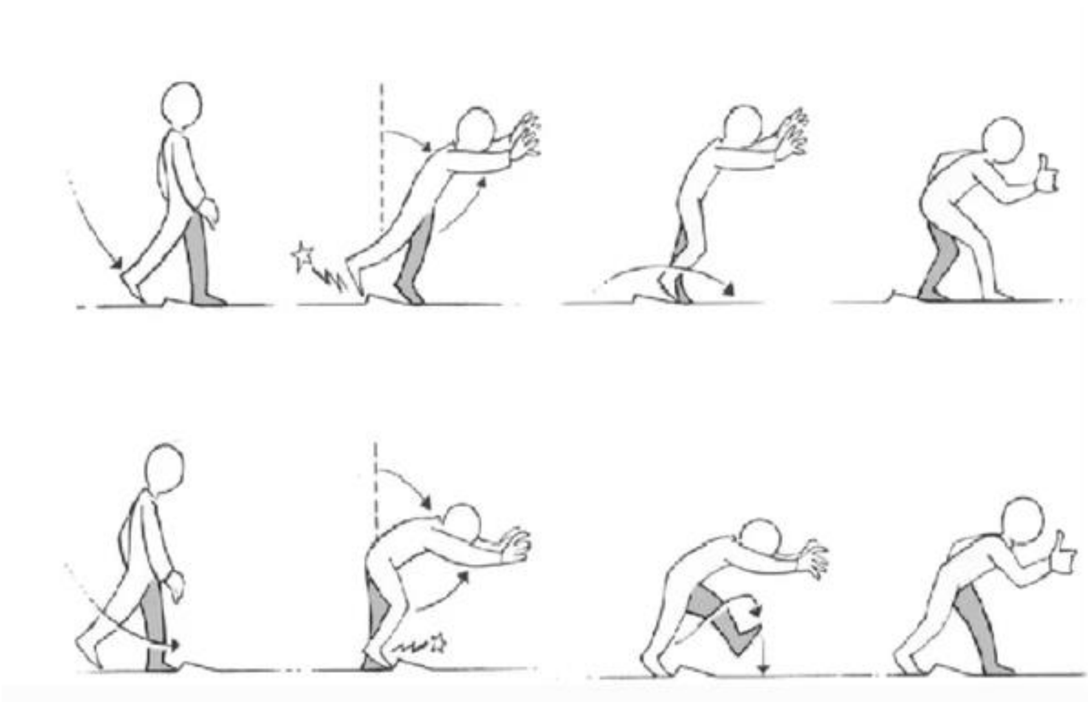
Using *X*COM, the margin of safety (MOS) has been introduced. MOS is defined as the minimum distance from *X*COM to the BOS boundaries (Hof et al., 2005). When using MOS in trip-related studies, the AP distance from the *X*COM to the closest edge (toe or heel of the closest foot) of the BOS is usually taken (Okubo et al., 2018).

Biomechanics of trip recovery

To recover from a trip, the suddenly acquired forward angular momentum of the upper body must be counteracted, COM velocity must be decreased, and the COM must be posteriorly shifted (Wang et al., 2012). Eng et al. (1994) described two main strategies during trip recovery as a lowering-hit strategy and an elevating-hit strategy (Figure 3). In the lowering-hit strategy, the tripping foot contacts the obstacle and is promptly lowered to the surface and placed posterior to the obstacle. In this strategy, the recovery step will be taken by the contralateral foot (non-tripping foot). In the elevating-hit strategy, the tripping foot contacts the obstacle and is placed anterior to the obstacle; thus, the same foot (tripping foot) is used to take the recovery step. When the subject's foot crosses over the obstacle without contacting the obstacle, Eng et al. (1994) identified it as the elevating-cross strategy. From these strategies, younger individuals commonly acquire the elevating-hit strategy, while elderly individuals prefer the lowering-hit strategy (Pijnappels et al., 2004). Moreover, the lowering-hit strategy is commonly observed during the initial trials during a series of repeated trip perturbations, while elevating-hit and elevating-cross strategies were commonly used during later trials (Okubo et al., 2018). When considering the timing of tripping the elevating-hit strategy was more observed once the trip was induced during the early swing, while the lowering-hit strategy was frequently observed once the trip was induced during the late swing (Eng et al., 1994).

Figure 3

Elevating-hit strategy (top row); lowering-hit strategy (bottom row) (Potocanac & Duysens, 2017)



Grabiner et al. (1996) and Pijnappels et al. (2004) described two phases in the trip recovery response. The duration from the obstacle contact to the positioning of the recovery foot on the ground is identified as the positioning phase (Grabiner et al., 1996). The duration from the obstacle contact until the toe-off of the support limb is known as the push-off phase (Pijnappels et al., 2004). During the positioning phase, the placement of the recovery foot anterior to the body's COM is crucial. Immediately after tripping, the body starts to rotate about the tripping foot. This resulted forward momentum can be successfully counteracted if the recovery foot is placed anterior to the COM. Immediately after the recovery foot is placed on the ground, it starts producing force to counterbalance the angular momentum that occurred due to the trip

(Pijnappels, Bobbert, & van Dieën, 2005). Just before the recovery foot is placed on the ground, the supporting limb provides a powerful push-off reaction producing force to create an opposing angular momentum, which takes some load off of the recovery limb (Pijnappels et al., 2004). As the support limb reduces more angular momentum, there will be less angular momentum for the recovery limb to counteract after it lands (Pijnappels et al., 2004). Moreover, the support limb aids the proper positioning of the recovery limb, contributing largely to a successful trip recovery (Pijnappels et al., 2004).

Following a trip, young adults sustain fewer falls than elderly adults (Pijnappels et al., 2004). In trip literature, the occurrence of a fall is determined in different ways, such as both feet coming off the ground (inability to regain balance), peak load cell force exceeding 30% of body weight (Yang & Pai, 2011), or load cell exceeded 200 N of force (Pijnappels et al., 2004). To prevent a fall, the individual must manage a certain number of factors with a shorter reaction time (Pavol et al., 2001). Proper recovery foot placement, increasing the BOS with the recovery step, reduction of forward angular velocity, reduction of trunk flexion (Bieryla et al., 2007), and creating adequate trunk extensor moment using the support limb (Pijnappels, Bobbert, & van Dieën, 2005) are some of the factors that contribute to a successful trip recovery. With repeated perturbation trials, increased post-trip MOS is considered an improvement in the balance recovery response (Okubo et al., 2018).

To prevent the inconsistencies due to participants' height, the step lengths (recovery step length or follow-up step length) are usually normalized to the subjects' height (Bhatt et al., 2013). In addition, before analyzing the step lengths during trip recovery, the participants' normal step length must be obtained as a baseline measurement (Wang et al., 2012). For that, an average (mean) of multiple step lengths during normal gait cycles is taken as the subject's average step length (Wang et al., 2012). If the recovery step length or follow-up step length exceeds six standard deviations (SD) of the subject's average step length, it is considered extreme instability. If both recovery step length and follow-up step length do not exceed 6 SD, it would be considered no significant loss of balance (Wang et al., 2012). Usually, the recovery step length is shown to be significantly longer than one's average step length (Wang et al., 2012). This could be explained by the abruptly acquired forward angular momentum following the trip and the necessity of expanding BOS in the direction of movement to restore balance.

Lower extremity muscle activity and trips

Following a trip, the coordination of multiple body segments is required to counteract the destabilizing forces to prevent a fall. This coordination is done and enhanced by the activity of muscles, especially the muscles in the trunk and the lower extremity (Pijnappels, Bobbert, & Van Dieen, 2005). These muscles aid in generating moments about the hip, knee, and ankle joints, re-establishing the suddenly acquired forward instability. Most studies conducted on muscle activity in trip biomechanics were focused on larger lower extremity muscles, such as the tibialis anterior (TA), medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (SO), gluteus maximus (GL), hamstrings complex, and quadriceps complex (Lee et al., 2019; Pijnappels, Bobbert, & van Dieën, 2005). The timing and sequence of muscle activity (muscle activity pattern) changes depending on the recovery strategy (Eng et al., 1994; Pijnappels et al., 2004). For example, increased biceps femoris muscle activity in the swing foot was evident during the elevating strategy, while its activity was not prominent during the lowering strategy (Eng et al., 1994). Further, a prolonged push-off phase and greater hamstring complex activity were observed during the elevating strategy, and a shorter push-off phase was observed in the lowering strategy (Pijnappels et al., 2004).

Schillings et al. (2000) studied behavioral strategies and muscle responses of the tripping leg in a group of young, healthy adults. The investigators categorized the behavioral strategies as elevating and lowering strategies similar to Eng et al. (1994) and observed the activity of TA, biceps femoris (BF), and rectus femoris (RF) during each strategy. During elevating strategy, they observed knee flexion and ankle dorsiflexion caused by the BF and TA, respectively, followed by activation of RF to cause knee extension during the recovery foot placement. Once the foot was promptly lowered to the ground during lowering strategy, the resulted knee extension and ankle dorsiflexion were mediated by RF and TA, respectively. (Schillings et al., 2000).

Pijnappels et al. (2005) investigated the support limb muscle activity upon tripping in a group of young adults. They studied the TA, MG, SO, vastus lateralis (VL), RF, semitendinosus (ST), BF, and GL muscles. They observed that all the swing leg joints (hip, knee, ankle) underwent flexion to clear the obstacle. Immediately following the trip, the earliest muscle responses were observed in BF and ST in the support limb, followed by GM, SO, and GL. These hamstring and gluteal muscles were responsible for creating hip extension moment (~52 Nm) following tripping, helping to reduce the trunk's forward angular velocity and cause a knee flexion moment in the support limb following tripping. Furthermore, the authors explained that this knee flexion aids in minimizing the forward rotation of the upper body segments. Eventually, the GM and SO muscles caused a large plantar flexion moment (~204 Nm), which is required for the push-off of the support limb. Finally, towards the end of the push-off phase, the activity of VL and RF created a knee extension moment. Moreover, these observed muscle responses in the support limb were fast (latencies 60–80 ms), especially on GL, ST, BF, GM, and SO muscles (Pijnappels, Bobbert, & van Dieën, 2005). Furthermore, these response times were closer to the response times observed in the tripping leg (Eng et al., 1994; Schillings et al., 2000). Thus, the authors concluded that the support limb muscle activity pattern is equally important in reducing forward trunk velocity to achieve a successful trip recovery. As the support limb takes more angular momentum during the push-off phase, the recovery limb would have less angular momentum to counteract after landing. Similarly, in a study conducted by Lee et al. (2019), the activity of TA, MG, LG, BF, and RF of the support limb was shown to be increased after the trip (Lee et al., 2019).

Lower extremity muscle fatigue and trips

Fatigue is the decrease in muscle force production due to central or peripheral reasons (Enoka, 2015). Peripheral fatigue, also known as physical fatigue, occurs due to insufficient action potential propagation following the lack or excess of metabolic components (Boyas & Guével, 2011). Muscle fatigue is commonly observed in the occupational categories such as firefighters, military personnel, roofers, construction workers, and manual material handlers (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor*, 2017). Undue fatigue alters postural control, including gait, trip incidence, trip severity, and trip recovery (Barbieri et al., 2014; Kodithuwakku Arachchige et al., 2020; Kodithuwakku Arachchige et al., 2021; Park et al., 2011).

Rashedi et al. (2016) studied healthy young adults' gait, trip risk, and TC before and after a series of ankle fatiguing exercises. For the ankle fatiguing protocol, the participants performed repeated isokinetic plantar flexion movements at 70% of their pre-fatigue maximum voluntary isometric contractions (MVIC). Fatigue was objectively determined once the participants' performance fell below 70% MVIC. The group observed decreased TC (~17%) following fatigue; thus, they suggested that the risk of tripping increases with fatigue (Rashedi et al., 2016).

Similarly, Barbieri et al. (2014) demonstrated that achieving the required TC is difficult with muscle fatigue; however, they investigated obstacle crossing, which is considered different from unexpected trips. In another previous study, the functional reflex activity of lower extremity muscles (vastus medialis, TA, and SO) of young, healthy adults was measured before and after ankle fatigue (Granacher et al., 2010). The ankle fatiguing protocol was performed on an isokinetic device with repeated ankle dorsiflexion and plantar flexion. The participants' pre-fatigue maximal torque at the ankle was initially measured, and ankle fatigue was marked once they reached below 50% of their maximal torque during the fatiguing protocol. The participants were subjected to treadmill-based trip perturbations before and after fatigue, and the functional reflex activity of the muscles was measured. A significant decrease in functional reflex activity in the TA was evident after fatigue, explaining the increased likelihood of unsuccessful trip recovery following muscle fatigue (Granacher et al., 2010).

Allin & Madigan (2020) studied the effect of a fatiguing manual material handling (MMH) task on trips and trip recovery among young, healthy adults. The participants were categorized into heavy MMH and light MMH groups, and the trip incidence, TC variability, maximum trunk flexion angle, and fall rate were studied before and after the two-hour-long fatiguing protocol, using 3D motion capture. The authors did not report a significant difference in the aforementioned parameters between the light and heavy MMH groups (Allin & Madigan, 2020). The group had incorporated only one trip trial into their study, which could be the reason for the insignificant findings between groups. Similarly, in a study conducted by Qu et al. (2020), 108 young, healthy adults were divided into three groups as no fatigue, mental fatigue, and physical fatigue and their trip recovery parameters (maximum trunk flexion angle, maximum trunk flexion velocity, and recovery step length) were measured. The researchers used a stand-to-sit exercise at a 40 Hz frequency to induce physical fatigue and a 90-minute-long computer-based visual task to induce mental fatigue. Although the recovery parameters were significantly different between the no fatigue and the mental fatigue groups, there were no significant differences between the no fatigue and physical fatigue groups. The authors explained that the subjective assessment of fatigue could have caused insignificant differences between the groups (Qu et al., 2020).

Role of anticipation on trips and trip recovery

Distraction or lack of anticipation of a trip hazard is identified as a significant cause of trip-induced falls (Elfering et al., 2018). Although the reactive responses to a perturbation are extremely decisive in the trip outcome, the proactive mechanisms also play a mandatory role (Wang et al., 2019). The reactive responses occur following the contact with the obstacle to correct the posture in a feedback loop. In contrast, proactive responses occur before contacting an obstacle (with the anticipation of a trip) in a feedforward mechanism. These proactive responses are shown to minimize the number of falls; however, these responses cannot entirely prevent the incidence of trips or falls (Wang et al., 2012).

Studies comparing expected and unexpected trip perturbations are rare in the previous trip-related literature, especially on young adults. Pater and coworkers (2015) assessed the fall rate, trip-recovery kinematics, and reaction time during expected and unexpected treadmill-based perturbations during walking in a group of older women (age 64 ± 7.1 years). The participants in the "expected" group were warned that "the treadmill will move in the next minute," while no such warning was provided to the "unexpected" group. The researchers observed that the participants in the "expected" group had a lesser fall rate, shorter reaction time, and better trip recovery kinematics (smaller trunk flexion angle, reduced trunk velocity) (Pater et al., 2015). In a study conducted by Pijnappels et al. (2001), fifteen young adults' gait kinematics and muscle activity were studied during unperturbed gait and following a warning of a possible trip. However, the researchers did not specify during which trials the subjects would be tripped. The participants were warned “a trip could occur during the next 50 trials”, but the participants were truly tripped during 10 of those forewarned trials. The authors did not observe any significant gait adjustments or muscle activity between unperturbed gait and the gait following forewarning, except for a minor increase in TC and step width in the forewarned trials (Pijnappels et al., 2001). Similarly, in another study conducted on young adults, Okubo et al. (2019) observed anticipatory adjustments such as short step length and increased TC while approaching the trip hazard. However, anticipation could cause a premature approach to the obstacle, and attempting to achieve a greater than required TC consumes additional energy, leading to undue lower extremity muscle fatigue (Barrett et al., 2010).

Rhea & Rietdyk (2011) further analyzed two previous studies to investigate the possible gait modifications (proactive adjustments) during repeated obstacle crossing. In this analysis, the authors expected a reduction in gait speed, step length, cadence, and an increase in TC with the expected trips. However, they did not identify any significant changes in the tripping limb or the supporting limb, except for an increase of TC in the tripping limb during later gait trials. After observing no supporting limb changes, the authors suggested that the tripping and supporting limbs could be controlled independently during obstacle crossing (Rhea & Rietdyk, 2011). Moreover, in another study, both proactive and reactive improvements were observed during 24 repeated tripping incidents in a group of elderly participants (Wang et al., 2019). In this study, the observed proactive improvements included decreased forward COM velocity and increased

TC, while reactive improvements included better post-trip forward stability and trunk control (Wang et al., 2019).

Dual tasking and trip biomechanics

As a major intrinsic factor that could impact postural control, attention is vastly studied in biomechanics. Earlier, postural control was thought to be a reflex-controlled or automatic process requiring minimal attention. However, this concept was disregarded with the developments during the past few decades upon understanding the significant requirement of attention for postural control (Maki & McIlroy, 2007). Increased prefrontal cortex activity during postural control is considered an indication of attentional processing (Yogev-Seligmann et al., 2008). The attentional requirement depends on the individual factors, the task/s at hand, and the surrounding environmental factors. Less attentional resources are needed for simpler tasks such as quiet standing on bilateral feet, while more attentional resources are required during dynamic tasks, perturbations, and alternating sensory outputs (Shumway-Cook & Woollacott, 2000). As postural tasks like walking or obstacle avoidance require considerable attention, an added secondary task causes divided attention in the worker. Currently, the DT paradigm is used as a common way to study attention in postural control (Lin et al., 2016). In the DT paradigm, postural control is considered the primary task and the added secondary performance (e.g., load-carrying) is considered the secondary task. The speed and accuracy of both task performances are usually affected in DT compared to ST (Lin et al., 2016). The successful accomplishment of these tasks depends on the complexity of each. In the event of varying task complexities, usually, the task with less attention demand will be favored due to the limited capacity of the brain (Chipunza & Mandeya, 2005). Therefore, DT is incorporated into research as a method to analyze executive functions of the brain as well. With the DT paradigm, executive functions such as task switching or selective attention are commonly assessed (Falbo et al., 2016). The incorporated secondary tasks in the DT paradigm could be cognitive (vision, hearing, speech, or memory-based task), motor (carrying an object), or both. While performing a secondary task in trip-related studies, the trip incidence and outcome vary depending on the nature of the added task (Inkol et al., 2018). Furthermore, young, healthy individuals perform better during DT than geriatric and clinical populations due to superior physical, physiological, and cognitive abilities (Brustio et al., 2017). Moreover, during DT, young, healthy adults favor the primary motor task (postural control) over the secondary ("posture first strategy"), which results in better performance in the postural control task (Bloem et al., 2001).

In a study conducted by Inkol et al. (2018), balance recovery responses during small and large support surface translations were assessed in healthy young adults, with and without DT. They incorporated congruent and incongruent auditory Stroop test as the simultaneous secondary task. In the congruent auditory Stroop test, the pitch and the word match (e.g., the word "high" is spoken in high pitch), and in the incongruent test, the pitch and the word do not match (e.g., the word "high" is spoken in low pitch). Trip recovery parameters, *X*COM, MOS, step onset, and step length were analyzed using 3D motion capture. The authors did not observe any association between the congruency of the auditory task and the response times. Although there were no significant differences in the recovery parameters between DT and ST, the response time for the auditory Stroop test was longer with larger perturbations during DT. Therefore, the authors mentioned that this study supports the "posture-first strategy" observed in young adults (Inkol et al., 2018). In another previous study (Norrie et al., 2002), a group of young adults' trip recovery responses was assessed with and without a concurrent visuomotor tracking tack. The trips were induced with platform translations, and the visuomotor tracking tack included continuous tracking of a moving target on a computer screen using a potentiometer (pursuit tracking). COP excursions and the MG and TA muscle activity were assessed using a force plate and EMG, respectively. They observed a pause in the cognitive task immediately after the postural perturbations. Moreover, towards the end of the perturbation (> 250 ms post-perturbation), the postural stability was affected during DT trials compared to the trials with ST. The authors explained that immediately after the perturbation, balance was maintained more in an "automatic" way, but as time progressed, there could be a requirement to involve more cognitive resources, which was not available due to the concurrent cognitive task; thus, the balance was deteriorated.

Rankin and coworkers (2000) compared the effect of a mentally demanding math task on trip recovery in young and elderly individuals using EMG. They used platform translations as the method of forward perturbation and a mental subtraction task (subtracting 3s, starting with the number 100) as the secondary cognitive task. Muscle activity of the gastrocnemius, TA, BF, RF, erector spinae, and rectus abdominis was assessed during trip recovery with and without DT. The researchers did not observe any significant differences in the onset of muscle activity (muscle latency) with and without DT. However, when both young and elderly groups were analyzed together, there was a significant reduction of gastrocnemius and TA activity with DT. Therefore, they concluded that fewer resources are available during DT for postural control, threatening postural stability (Rankin et al., 2000).

In a study performed by Paran et al. (2020), the parameters of the recovery step (step reaction initiation time, step length, step swing time, and MOS) of healthy young adults were assessed during DT and ST using 3D motion capture. Surface translations of different magnitudes (extra-small to extra-large) were included as the trip perturbations, and serial subtractions by seven was included as the cognitive task. However, they did not find any significant differences in the cognitive task performance or the recovery parameters between DT and ST conditions. Thus, the authors suggested that the young adults may have sufficient resources to perform both tasks simultaneously and were able to switch between the two tasks successfully (Paran et al., 2020).

Effect of standing height and VR-based training on static postural stability

Postural instability is highly prevalent in the working population upon exposure to heights (Salassa & Zapala, 2009). Ergonomic populations such as roofers, construction workers, and firefighters are frequently exposed to heights, hence they are more vulnerable to balance decrements at altitudes. For instance, in 2018, 338 of the total 1008 deaths that occurred among construction workers due to falls from heights (BLS, *National Census of Fatal Occupational Injuries.*, 2018). Therefore, many researchers have focused on the role of balance training in preventing falls from a height. Previously, balance training has been done with the use of traditional methods such as core strength training (Yu et al., 2017), hydrotherapy (Geytenbeek, 2002), and treadmill walking (Cha et al., 2016). However, these training methods may be impractical, time-consuming, sophisticated, and less convenient when applied to ergonomic settings (Geytenbeek, 2002). Due to its simulation ability, affordability, and convenience, VR-based training is currently considered a potential training tool for fall prevention (Cleworth et al., 2012; Simeonov et al., 2005). Moreover, VR is identified as a great alternative to expose individuals to different environments they otherwise avoid due to fear (Cleworth et al., 2012). Additionally, in occupations such as roofing, construction, and firefighting, where training in real environments is not convenient or safe, balance training in virtual environments (VEs) is more feasible and practical (Chander et al., 2020; Shendarkar et al., 2008). However, thus far, the studies conducted on the application of VR-based training have mainly focused on the elderly and pathological populations. The number of studies conducted on young, healthy adults that could be applied to the occupational population is minimal. Moreover, the few studies conducted on the occupational population were limited to the training at ground level (Lavender et al., 2019). Due to this dearth of literature, little is known about applying VR-based training at an altitude in the ergonomic population.

Simeonov et al. (2005) conducted a study on a young, healthy sample, in which they were exposed to 0 m, 3 m, and 9 m real and matched virtual heights on stable and unstable (foam) surfaces. The researchers assessed the participants' postural sway using a force platform in the anteroposterior and mediolateral directions, along with some physiological parameters (heart rate, skin conductance response) and subjective assessments (perceived anxiety, perceived risk of falling, perceived potential injury risk). The static postural stability deteriorated with increasing height in real and virtual environments, more pronounced on the unstable surface. The participants reported a mild perceived anxiety and fall risk in both environments that increased with height. Therefore, the authors concluded VR is a realistic height simulator. Moreover, perceived potential injury risk increasing with height was reported in both environments but was more pronounced in the real environment. Although the skin conductance analysis elicited similar effects in both real and VE, heart rate was more increased in the real environment (Simeonov et al., 2005). While using VR, the participants' posture will entirely be dependent on the somatosensory and vestibular sensory systems. This could be a reason for the differences observed between the real and virtual environments. In a similar study by Cleworth et al. (2012), young, healthy participants' static balance, psycho-social state, and electrodermal activity were assessed upon exposure to 0.8 m and 3.2 m real and virtual heights. The group observed increased postural sway, perceived imbalance, fear, anxiety, and electrodermal activity at both real and virtual heights. Thus, they suggested that the virtually generated heights elicit similar postural, psychosocial, and autonomic responses similar to the exposure to physical heights. Further, the static postural stability, electrodermal activity, and fear of height increased as the height increased and were more pronounced in real environments than the virtual environments (Cleworth et al., 2012).

Chander et al. (2020) conducted a study with young, healthy participants who were exposed to a real environment at 0 feet and VEs at 0 feet, 40 feet, and 120 feet. The participants' static postural stability was assessed using a force plate. They observed significant balance decrements in VEs compared to the real environment. This was explained by the visual obscureness caused by the head mount display (HMD) used to administer the VEs (Chander et al., 2020). Greater postural instability in the VEs was observed by other investigators as well, even when the HMD weight was controlled within the trials (Akizuki et al., 2005; Horlings et al., 2009). In the Horlings et al. (2009) study, young adults' static stability in real and virtual environments was assessed in eyes-open/closed conditions on a firm surface and a foam surface, using an instrument that contains two gyroscopes (SwayStar™, Balance International Innovation GmbH, Switzerland). Here, greater balance decrements were observed in the VEs and on the unstable (foam) surface. Interestingly, the balance decrements observed in the VEs were closer to the balance decrements observed in the eyes closed conditions. Therefore, the authors concluded that VR causes postural instability similar to closing someone's eyes (Horlings et al., 2009). Although exposure to virtual heights triggers some unsatisfactory emotions and effects, which probably occur due to sensory conflicts, as mentioned before, VR-based training has many advantages over training in real environments (Cleworth et al., 2012). Hence, VR itself could be a training tool to overcome such adverse effects.

Effect of acrophobia on postural stability and cognitive performance

According to the American Psychiatric Association, acrophobia is the extreme fear of heights, similar to panic disorders, affecting > 5% of the general population (American Psychiatric Association, 1994). Fear of heights could cause limited motion, loss of balance, and falls (Huppert et al., 2020). Therefore, the working population must be trained to counteract this fear in order to prevent falling from heights. Individuals with acrophobia experience many symptoms related to increased sympathetic activity, such as sweating, tachycardia, hyperventilation, and tremors (Cleworth et al., 2012; Diemer et al., 2016). Furthermore, the individuals who experience acrophobia in real environments usually experience a similar feeling upon exposure to the virtual heights (Diemer et al., 2016).

While some individuals are aware of their fear of heights, some manage to climb to an elevation but later develop fear after the height exposure. Diemer et al. (2016) exposed two groups of acrophobic and healthy controls to 0 m and 13.9 m virtual heights while physically standing on a 5 cm thick wooden board. At the virtual altitude, the participants were advised to walk toward the edge of the real wooden plank to simulate them standing at the edge of 13.9 m height. Once the participants reached the edge, they were asked to look down and straight forward, five trials each. The participants' HR, respiratory rate, saliva cortisol levels, skin conductance level, and subjective fear ratings were measured before, during, and after the virtual height challenge. The individuals with acrophobia demonstrated a significant increase in HR, skin conductance, and fear ratings, while the control group also showed significantly increased HR and skin conductance. Salivary cortisol levels were not significantly increased in either group, which was against their hypothesis (Diemer et al., 2016). This study demonstrates that acrophobia is not limited to physical heights; it could also develop in virtual heights. Further, it shows that even healthy individuals could develop features of acrophobia to a certain extent. However, in a study that used different virtual heights, the individuals with fear of heights demonstrated greater postural instability than those without fear of heights (Newman et al., 2020). The results were attributed to their greater anxiety, stress, and increased stress-induced cortisol secretion (Newman et al., 2020). Cortisol disrupts the activity of the prefrontal cortex area, which regulates a significant proportion of major executive functions (attention, working memory, task switching, and response inhibition). Similarly, dynamic balance at physical and virtual heights was examined by Peterson et al. (2018). The participants walked on a wooden balance beam (2.5 cm off the ground), virtual-low (2.5 cm virtual height), and virtual-high (15 m virtual height) environments. Participants' dynamic balance was decreased at virtual-high conditions compared to the other two conditions. Moreover, they observed a significant reduction in electroencephalography (EEG) readings in the anterior cingulate area, which contributes to detecting loss of balance.

Except for the fear and increased sympathetic activity, exposure to virtual heights triggers other emotions, including anxiety and stress (Cleworth et al., 2012; Fadeev et al., 2020). Fadeev et al. (2020) exposed young, healthy participants to different virtual heights, including an 80-story skyscraper and a roller coaster. The participants demonstrated high acute emotional stress levels and increased sympathetic activity upon exposure to heights. Since fear and anxiety are associated with reduced executive functions like attention switching (Arnsten, 2009), such anxiety-related situations caused a decline in postural control (Cleworth et al., 2012; Newman et al., 2020; Peterson et al., 2018). Previous experience of a fall, fear of falling, and fear of heights (physical or virtual height) are major anxiety-provoking situations related to posture (Benjuya et al., 2004; Cleworth et al., 2012; Wong et al., 2007). In addition, the emotional reactivities triggered by the exposure to virtual heights could induce motor and executive dysfunction (Cleworth et al., 2012; Peterson et al., 2018). For instance, maintaining static postural stability (Cleworth et al., 2012) and dynamic postural stability tasks such as gait (Peterson et al., 2018) are shown to be affected.

Zaback et al. (2019) used a hydraulic lift to assess the effect of a height-induced postural threat in a group of young healthy adults at 0.8 m and 3.2 m heights. The participants were standing on their toes, towards the middle of the standing surface at 0.8 m and the edge of the platform at 3.2 m height. COP excursions, GRF, moments, lower extremity muscle activity (TA and SO), electrodermal activity, and subjective assessments (cognitive state, fear of fall/ anxiety, balance confidence) were assessed at each trial. Although the investigators expected to observe balance decrements at an altitude, the participants' balance was preserved at the height. They observed high frequency, lower magnitude COP excursions, and backward shifting of COP at the altitude as a mechanism to maintain balance. The participants were exposed to five trials of each condition, but the researchers did not observe any balance changes with repeated exposure. However, the participants' emotional status was more threatened with elevation and repeated exposure to the elevation. In addition, an increased co-contraction of TA and SO muscles was evident upon examining the muscle activity (Zaback et al., 2019).

Brown and colleagues (2006) recruited two groups of young and elderly adults, placed them on a hydraulic lift platform, and introduced them to 0.17 m and 1.4 m heights in the middle and the edge of the platform. The testing conditions were low-middle, low-edge, high-middle, and high-edge, where low-middle elicited the least and high-edge elicited the greatest postural threat. Participants stood still at each location for 15 s, and their kinematic data, COP excursions, GRF, moments, muscle activity (TA, SO), and skin conductance were measured at each condition. The skin conductance increased with height and on edge in both groups, indicating anxiety. Most importantly, similar to the Zaback et al. (2019) study, the researchers observed increased frequency and decreased magnitude of postural sway as the postural threat increased in both young and adult groups. This was explained by the increased co-contraction of the agonist/antagonist muscles, resulting in a stiff ankle joint. Moreover, as the postural threat (and therefore anxiety) increases, the participants tend to acquire a backward lean, shifting their COP posteriorly. Due to this backward lean, at elevation, the anterior muscle's (TA) activity was greatly increased to prevent a backward fall (Brown et al., 2006). In a similar previous study (Adkin et al., 2002), young adults were exposed to the same low-edge, high-middle, and high-edge conditions using a platform. COP excursions, muscle activity (TA, MG, SO), and subjective measurements (confidence, stability, anxiety) were measured during a rise to toes task. Significant postural adjustments were observed at the "high" and the "edge" positions. These postural adjustments co-existed with the situations where the participants' confidence and stability were marked as low, and their anxiety was marked high (Adkin et al., 2002). Such anticipatory postural adjustments upon exposure to heights, including co-contraction of the lower extremity muscles, are mediated by the CNS to mitigate the postural instabilities.

A limited number of studies were conducted on training individuals at an altitude. Cyma-Wejchenig et al. (2020) recruited construction workers (age 22-47 years) who usually work at heights. The participants were divided into a training group and a control group; the training group was exposed to twelve 30-minute-long training sessions over six weeks. They were trained at the ground level and 1 m virtual height during quiet standing. The participants' COP excursions were measured using a force plate before and after training. The results revealed that the post-training COP excursions of the training group were significantly lower than the pre-training values. Therefore, the researchers suggested VR-based proprioception training as a great way to improve static postural stability and may potentially replace the traditional training methods (Cyma-Wejchenig et al., 2020).

Addressing acrophobia includes gradual repeated exposure to heights (American Psychiatric Association, 1994), but exposing an agitated individual to a physical height could endanger their life. Conveniently, VR has been introduced to assess, train, and address the fear of falling at heights due to its convenience and the absence of physical danger (Wang et al., 2019; Wang et al., 2018). As conflicting visual input is the major reason for acrophobia, VR could be a suitable solution to address it. Thus, VR is used as a training tool to overcome the fear of falling from heights, known as VR exposure therapy (VERT) (Fu et al., 2019). Similar to the training to overcome the fear of falling, VR-based training could effectively overcome height-related anxiety (Emmelkamp et al., 2001). However, the appropriate duration of training and retention is yet debatable. When attempting VR-based training in young, healthy adults, it may not require prolonged training as the geriatric or clinical populations (Elion et al., 2015). In a previous study, young adults were trained on balance maintenance on a moving platform synchronized with a VE. The training was carried out on a single day, and the exposure time was 24 minutes. COP excursions were assessed during, immediately after, and 24 hours, four weeks, and 12 weeks post-training to assess retention. The COP excursions were significantly lower post-training and were retained after 24 hours, four weeks, and 12 weeks (Elion et al., 2015). Therefore, even a short, single training session could improve the postural stability in young healthy adults.

As mentioned earlier, exposure to virtual heights triggers anxiety and stress (Cleworth et al., 2012; Fadeev et al., 2020). Such emotions are associated with reduced attention, cognitive processing, and cognitive performance while increasing the cognitive load (Eysenck et al., 2007; Peterson et al., 2018). The prefrontal cortex regulates a significant proportion of the brain's major executive functions (working memory, task switching, response inhibition). However, the prefrontal cortex is significantly affected by stress hormones released upon exposure to heights, affecting executive functions (Arnsten, 2009). The impact of virtual heights on executive function was studied by Newman et al. (2020), exposing young, healthy participants to different virtual heights (ground level, low VR height, and high VR height) while sitting on a chair. The participants' appraisal of height was determined using a height interpretation questionnaire, in which a high negative appraisal indicates fear of heights. In the individuals with a high negative appraisal of height, the executive functions (working memory and response inhibition) were significantly affected at VR heights compared to the VR ground level. The authors explained that the increased stress-induced cortisol levels could have affected cognitive functions (Arnsten, 2009).

Effect of dual-tasking on static postural stability and cognitive performance

In a previous section, the effect of DT on dynamic stability, balance recovery, and cognitive performance was discussed. Similarly, DT is shown to affect static postural stability in real and virtual environments (Mitra et al., 2013; Walsh, 2021). In the ergonomic population, simultaneous performance of cognitive tasks is extremely common. Such cognitive tasks could be reading a notice, identifying a hazard sign, performing a mental math task, or more. The workers may have to perform these tasks on the ground level or while working at an altitude. As mentioned, balance maintenance at an altitude is more challenging than on the ground level.

Further, balance decrements at an altitude cause catastrophic results due to the possibility of falls. Similarly, failing to perform the concurrent cognitive task could result in dangerous outcomes (e.g., failing to identify a hazard sign). Thus, the workers must be trained to perform successful DT to improve their productivity and minimize possible injuries. Like any other situation involving risky physical environments, VR seems to be a promising solution to train workers on DT at an altitude. In the previously described Cyma-Wejchenig et al. (2020) study, the construction workers' static postural stability was assessed at the ground level and 1 m virtual height during quiet standing upon exposure to 12, 30-minute-long training sessions over six weeks. Further, the group was assessed while performing a cognitive task, which included counting down from the number 200 by 3's. The researchers observed improved balance maintenance post-training, even during the DT conditions (Cyma-Wejchenig et al., 2020). Walsh (2021) compared the effect of ST and cognitive DT on static postural stability in young and older individuals. For the cognitive task, the participants counted backward in increments of 7s from a random number that appeared on a television screen. The participants' COM was tracked using an inertial measurement unit, which demonstrated deteriorated static postural stability in the DT condition in both young and old categories (Walsh, 2021). In a study done by Mitra et al. (2013), the static postural stability of young, healthy individuals was studied with and without DT. One-half of the participants were quietly standing while wearing an HMD with a black screen. The other half of the participants completed a visuo-postural alignment task, in which they wore an HMD and aligned two virtual crosshairs together by moving their head/body. Both groups performed a simultaneous spatial or non-spatial cognitive task. The spatial cognitive task included selecting true/false answers using a mouse about the university's layout, while the non-spatial cognitive task included questions on the organization of the university. Postural sway variables were measured using the Polhemus Fastrak motion tracker, and the speed and accuracy of the responses to the cognitive tasks were measured. There were no significant differences between the accuracy of tasks, but the reaction time was longer for the spatial cognitive task. Anteroposterior and mediolateral postural sway increased during DT conditions during quiet stance but not during the visuo-postural alignment task (Mitra et al., 2013).

Helfer et al. (2020) assessed young adults' and middle-aged adults' static postural stability during cognitive DT. The cognitive task included listening and repeating the sentences heard in challenging acoustic conditions (presence of other sentences in the environment) and non-challenging acoustic conditions (steady-state noise). Postural sway was assessed using a piezoelectric force platform in the normal quiet stance and tandem stance. Postural stability was more affected in both stances when the DT was performed in the challenging acoustic conditions, which was more pronounced in middle-aged adults. The authors attributed this finding to the requirement for greater efforts to listen under challenging acoustic conditions (high attention demand), leaving limited resources for postural control (Helfer et al., 2020).

In another study, a group of young adults' static postural stability was measured using a force plate (Imaizumi et al., 2018). The participants were divided into two groups; one group was advised to observe visual feedback of their postural sway provided on an HMD. The other group was advised to attempt and voluntarily control the visual feedback of their postural sway to maintain their postural stability better. The postural sway was significantly greater in the group that attempted to control the visual feedback and the postural sway (Imaizumi et al., 2018). While the authors explained these findings by having a concurrent cognitive task, it could also be explained by the "constrained action hypothesis" (Wulf & Lewthwaite, 2016). According to this hypothesis, during internal focus (focusing on their body), the individuals consciously attempt to control their posture, which disrupts the natural postural control processes. Contrarily, in external focus, the individuals are focused on an external target, allowing postural control to occur naturally and subconsciously, thus, generating better outcomes (Wulf & Lewthwaite, 2016). This hypothesis was confirmed by many researchers independently, using distinct methods, such as EMG. The studies that used EMG showed increased lower extremity EMG activity with internal focus, indicating a higher muscle force production (Lohse et al., 2011). Comparatively, the muscle force production during the external focus condition was less. Therefore, it was suggested that, with an external focus, the performance occurs smoothly and efficiently, reflected by less muscle force production (Lohse et al., 2011). Along with this concept, DT is now considered a great way to promote external focus (Wulf et al., 2001), preventing their deliberate attempts to manipulate posture, which allows better postural control (Gabriele Wulf et al., 2003).

Conclusion

Maintaining proper postural control is extremely important to prevent falls at the workplace. Such falls could occur due to many reasons, including trips, dual tasking, fatigue, and exposure to altitudes. Identifying these potential external/ internal perturbations and training workers to achieve proper postural control upon the destabilizing factors is mandatory. VR-based balance training is becoming popular due to its convenience, feasibility, and ability to regenerate challenging environments. However, there is a recognizable gap in the literature regarding the studies conducted on young, healthy adults, who comprise a significant proportion of the working population. Therefore, this project plans to address some of those lacking aspects, such as the factors affecting trip incidence, severity, and recovery and VR technology as a training tool for fall prevention in the ergonomic population.

References

Abelson, J. L., & Curtis, G. C. (1989). Cardiac and neuroendocrine responses to exposure therapy in height phobics: Desynchrony within the ‘physiological response system.’ *Behaviour Research and Therapy*, *27*(5), 561–567. https://doi.org/https://doi.org/10.1016/0005-7967(89)90091-0

Abuin-Porras, V., Villafañe, J. H., Jiménez-Antona, C., Palacios, A., Martínez-Pascual, B., & Rodríguez-Costa, I. (2018). Relationship between attention and balance: a dual-task condition study in children. *Journal of Exercise Rehabilitation*, *14*(3), 349–355. https://doi.org/10.12965/jer.1836142.071

Adkin, A., Frank, J., Carpenter, M., & Peysar, G. (2002). Fear of failing modifies anticipatory postural control. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *143*, 160–170. https://doi.org/10.1007/s00221-001-0974-8

Akizuki, H., Uno, A., Arai, K., Morioka, S., Ohyama, S., Nishiike, S., Tamura, K., & Takeda, N. (2005). Effects of immersion in virtual reality on postural control. *Neuroscience Letters*, *379*(1), 23–26. https://doi.org/https://doi.org/10.1016/j.neulet.2004.12.041

Allin, L. J., & Madigan, M. L. (2020). Effects of Manual Material Handling Workload on Measures of Fall Risk. *IISE Transactions on Occupational Ergonomics and Human Factors*, *8*(3), 155–165. https://doi.org/10.1080/24725838.2020.1850552

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (A. P. Association (Ed.); 4th ed.).

Arnsten, A. F. T. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Barbieri, F. A., dos Santos, P. C. R., Simieli, L., Orcioli-Silva, D., van Dieën, J. H., & Gobbi, L. T. B. (2014). Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing. *Gait and Posture*, *39*(3), 985–990. https://doi.org/10.1016/j.gaitpost.2013.12.021

Barrett, R. S., Mills, P. M., & Begg, R. K. (2010). A systematic review of the effect of ageing and falls history on minimum foot clearance characteristics during level walking. *Gait & Posture*, *32*(4), 429–435. https://doi.org/https://doi.org/10.1016/j.gaitpost.2010.07.010

Begg, R., Best, R., Dell'Oro, L., & Taylor, S. (2007). Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls. *Gait & Posture*, *25*(2), 191–198. https://doi.org/https://doi.org/10.1016/j.gaitpost.2006.03.008

Benjuya, N., Melzer, I., & Kaplanski, J. (2004). Aging-Induced Shifts From a Reliance on Sensory Input to Muscle Cocontraction During Balanced Standing. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences*, *59*, 166–171. https://doi.org/10.1093/gerona/59.2.M166

Bhatt, T., Wang, T.-Y., Yang, F., & Pai, Y.-C. (2013). Adaptation and generalization to opposing perturbations in walking. *Neuroscience*, *246*, 435–450. https://doi.org/https://doi.org/10.1016/j.neuroscience.2013.04.013

Bieryla, K. A., Madigan, M. L., & Nussbaum, M. A. (2007). Practicing recovery from a simulated trip improves recovery kinematics after an actual trip. *Gait & Posture*, *26*(2), 208–213. https://doi.org/https://doi.org/10.1016/j.gaitpost.2006.09.010

Bloem, B. R., Valkenburg, V. V, Slabbekoorn, M., & Willemsen, M. D. (2001). The Multiple Tasks Test: Development and normal strategies. *Gait & Posture*, *14*(3), 191–202. https://doi.org/https://doi.org/10.1016/S0966-6362(01)00141-2

Boyas, S., & Guével, A. (2011). Neuromuscular fatigue in healthy muscle: Underlying factors and adaptation mechanisms. *Annals of Physical and Rehabilitation Medicine*, *54*(2), 88–108. https://doi.org/https://doi.org/10.1016/j.rehab.2011.01.001

Brown, L. A., Polych, M. A., & Doan, J. B. (2006). The effect of anxiety on the regulation of upright standing among younger and older adults. *Gait and Posture*, *24*(4), 397–405. https://doi.org/10.1016/j.gaitpost.2005.04.013

Brustio, P. R., Magistro, D., Zecca, M., Rabaglietti, E., & Liubicich, M. E. (2017). Age-related decrements in dual-task performance: Comparison of different mobility and cognitive tasks. A cross sectional study. *PloS One*, *12*(7), e0181698–e0181698. https://doi.org/10.1371/journal.pone.0181698

Bureau of Labor Statistics, National Census of Fatal Occupational Injuries. (2018). https://www.bls.gov/iif/oshwc/cfoi/cftb0322.htm

Bureau of Labor Statistics. (2020). A Look at Work Injuries, Illnesses, and Fatalities. https://www.bls.gov/opub/ted/2020/a-look-at-work-injuries-illnesses-and-fatalities-on-workers-memorial-day.htm

Burg, J., Pijnappels, M., & Van Dieen, J. (2005). Out-of-plane trunk movements and trunk muscle activity after a trip during walking. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *165*, 407–412. https://doi.org/10.1007/s00221-005-2312-z

Cha, H.-G., Kim, T.-H., & Kim, M.-K. (2016). Therapeutic efficacy of walking backward and forward on a slope in normal adults. *Journal of Physical Therapy Science*, *28*(6), 1901–1903. https://doi.org/10.1589/jpts.28.1901

Chander, H., Garner, J. C., & Wade, C. (2014). Impact on balance while walking in occupational footwear. *Footwear Science*, *6*(1), 59–66. https://doi.org/10.1080/19424280.2013.834979

Chander, H., Shojaei, A., Deb, S., Kodithuwakku Arachchige, S. N. K., Hudson, C., Knight, A. C., & Carruth, D. W. (2020). Impact of Virtual Reality–Generated Construction Environments at Different Heights on Postural Stability and Fall Risk. *Workplace Health & Safety*, 2165079920934000. https://doi.org/10.1177/2165079920934000

Chipunza, C., & Mandeya, A. (2005). Dual-Task Processing: Effects of Task Difficulty and Stimulus Similarity on Dual-Task Performance. *South African Journal of Psychology*, *35*(4), 684–702. https://doi.org/10.1177/008124630503500405

Cleworth, T. W., Horslen, B. C., & Carpenter, M. G. (2012). Influence of real and virtual heights on standing balance. *Gait & Posture*, *36*(2), 172–176. https://doi.org/https://doi.org/10.1016/j.gaitpost.2012.02.010

Ćosić, K., Popović, S., Šarlija, M., Mijić, I., Kokot, M., Kesedžić, I., Strangman, G., Ivković, V., & Zhang, Q. (2019). New Tools and Methods in Selection of Air Traffic Controllers Based on Multimodal Psychophysiological Measurements. *IEEE Access, 7*, 174873–174888. https://doi.org/10.1109/ACCESS.2019.2957357

Cyma-Wejchenig, M., Tarnas, J., Marciniak, K., & Stemplewski, R. (2020). The influence of proprioceptive training with the use of virtual reality on postural stability of workers working at height. *Sensors (Switzerland)*, *20*(13), 1–17. https://doi.org/10.3390/s20133731

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Diemer, J., Lohkamp, N., Mühlberger, A., & Zwanzger, P. (2016). Fear and physiological arousal during a virtual height challenge—effects in patients with acrophobia and healthy controls. *Journal of Anxiety Disorders*, *37*, 30–39. https://doi.org/https://doi.org/10.1016/j.janxdis.2015.10.007

Dong, X. (2005). Long workhours, work scheduling and work-related injuries among construction workers in the United States. *Scandinavian Journal of Work, Environment & Health*, *31*(5), 329–335. http://www.jstor.org/stable/40967512

Elfering, A., Kottwitz, M. U., Häfliger, E., Celik, Z., & Grebner, S. (2018). Interruptions, Unreasonable Tasks, and Quality-Threatening Time Pressure in Home Care: Linked to Attention Deficits and Slips, Trips, and Falls. *Safety and Health at Work*, *9*(4), 434–440. https://doi.org/https://doi.org/10.1016/j.shaw.2018.02.001

Elion, O., Sela, I., Bahat, Y., Siev-Ner, I., Weiss, P. L. (Tamar), & Karni, A. (2015). Balance maintenance as an acquired motor skill: Delayed gains and robust retention after a single session of training in a virtual environment. *Brain Research*, *1609*, 54–62. https://doi.org/https://doi.org/10.1016/j.brainres.2015.03.020

Emmelkamp, P., Bruynzeel, M., Drost, L., & Mast, C. (2001). Virtual Reality Treatment in Acrophobia: A Comparison with Exposure in Vivo. *Cyberpsychology & Behavior : The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society*, *4*, 335–339. https://doi.org/10.1089/109493101300210222

Employed persons by detailed industry and age. (2020). https://www.bls.gov/cps/cpsaat18b.htm

Employer-Reported Workplace Injuries and Illnesses. (2019). https://www.bls.gov/news.release/archives/osh_11072019.pdf

Eng, J., Winter, D., & Patla, A. E. (1994). Strategies for Recovery from a Trip in Early and Late Swing during Human Walking. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *102*, 339–349. https://doi.org/10.1007/BF00227520

Enoka, R. M. (2015). *Neuromechanics of Human Movement* (5th ed.). Champaign.

Eysenck, M., Derakshan, N., Santos, R., & Calvo, M. (2007). Anxiety and Cognitive Performance: Attentional Control Theory. *Emotion (Washington, D.C.)*, *7*, 336–353. https://doi.org/10.1037/1528-3542.7.2.336

Fadeev, K. A., Smirnov, A. S., Zhigalova, O. P., Bazhina, P. S., Tumialis, A. V, & Golokhvast, K. S. (2020). Too Real to Be Virtual: Autonomic and EEG Responses to Extreme Stress Scenarios in Virtual Reality. *Behavioural Neurology*, *2020*, 5758038. https://doi.org/10.1155/2020/5758038

Falbo, S., Condello, G., Capranica, L., Forte, R., & Pesce, C. (2016). Effects of Physical-Cognitive Dual Task Training on Executive Function and Gait Performance in Older Adults: A Randomized Controlled Trial. *BioMed Research International*, *2016*, 5812092. https://doi.org/10.1155/2016/5812092

Fu, Q., Hou, H., Jiang, D., & Liu, Z. (2019). *The Design of Immersion Acrophobia Adjuvant Therapy System (IAATS)* (pp. 447–455). https://doi.org/10.1007/978-981-13-8138-6_38

Garman, C. R., Franck, C. T., Nussbaum, M. A., & Madigan, M. L. (2015). A bootstrapping method to assess the influence of age, obesity, gender, and gait speed on probability of tripping as a function of obstacle height. *Journal of Biomechanics*, *48*(6), 1229–1232. https://doi.org/https://doi.org/10.1016/j.jbiomech.2015.01.031

Geytenbeek, J. (2002). Evidence for effective hydrotherapy. *Physiotherapy*, *88*(9), 514–529. https://doi.org/10.1016/S0031-9406(05)60134-4

Gjoreski, M. (2016). *Continuous Stress Monitoring Using a Wrist Device and a Smartphone*. *September 2016*, 86. https://www.researchgate.net/publication/308611962

Grabiner, M. D., Feuerbach, J. W., & Jahnigen, D. W. (1996). Measures of paraspinal muscle performance do not predict initial trunk kinematics after tripping. *Journal of Biomechanics*, *29*(6), 735–744. https://doi.org/https://doi.org/10.1016/0021-9290(95)00142-5

Granacher, U., Gruber, M., Förderer, D., Strass, D., & Gollhofer, A. (2010). Effects of ankle fatigue on functional reflex activity during gait perturbations in young and elderly men. *Gait & Posture*, *32*(1), 107–112. https://doi.org/https://doi.org/10.1016/j.gaitpost.2010.03.016

Granacher, U., Wolf, I., Wehrle, A., Bridenbaugh, S., & Kressig, R. W. (2010). Effects of muscle fatigue on gait characteristics under single and dual-task conditions in young and older adults. *Journal of NeuroEngineering and Rehabilitation*, *7*(1), 56. https://doi.org/10.1186/1743-0003-7-56

Helfer, K. S., Freyman, R. L., van Emmerik, R., & Banks, J. (2020). Postural Control While Listening in Younger and Middle-Aged Adults. *Ear and Hearing*, *41*(5), 1383–1396. https://doi.org/10.1097/AUD.0000000000000861

Hof, A. L., Gazendam, M. G. J., & Sinke, W. E. (2005). The condition for dynamic stability. *Journal of Biomechanics*, *38*(1), 1–8. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.03.025

Holding, D. (1983). Stress and fatigue in human performance. In R. Hockey (Ed.), *Fatigue* (pp. 145–164). John Wiley and Sons.

Horak, F .B. (1987). Clinical measurement of postural control in adults. *Physical Therapy*, *67*(12), 1881–1885. https://doi.org/10.1093/ptj/67.12.1881

Horak, Fay B. (2006). Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing*, *35*(suppl_2), ii7–ii11. https://doi.org/10.1093/ageing/afl077

Horlings, C., Carpenter, M., Küng, U., Honegger, F., Wiederhold, B., & Allum, J. (2009). Influence of VR on postural stability during movements of quiet stance. *Neuroscience Letters*, *451*, 227–231. https://doi.org/10.1016/j.neulet.2008.12.057

Huppert, D., Grill, E., & Brandt, T. (2012). Down on heights? One in three has visual height intolerance. *Journal of Neurology*, *260*. https://doi.org/10.1007/s00415-012-6685-1

Huppert, D., Wuehr, M., & Brandt, T. (2020). Acrophobia and visual height intolerance: advances in epidemiology and mechanisms. *Journal of Neurology*, *267*(1), 231–240. https://doi.org/10.1007/s00415-020-09805-4

Imaizumi, S., Asai, T., Hiromitsu, K., & Imamizu, H. (2018). Voluntarily controlled but not merely observed visual feedback affects postural sway. *PeerJ*, *2018*(4), 1–22. https://doi.org/10.7717/peerj.4643

Incidence rates of nonfatal occupational injuries and illness by industry and case types, Bureau of labor statistics, US department of labor. Available from: https://www.bls.gov/. (2017).

Inkol, K. A., Huntley, A. H., & Vallis, L. A. (2018). Do perturbation-evoked responses result in higher reaction time costs depending on the direction and magnitude of perturbation? *Experimental Brain Research, 236*(6), 1689–1698. https://doi.org/10.1007/s00221-018-5249-8

Jacobs, J. V, & Horak, F. . B. (2007). Cortical control of postural responses. *Journal of Neural Transmission (Vienna, Austria : 1996)*, *114*(10), 1339–1348. https://doi.org/10.1007/s00702-007-0657-0

Karamanidis, K., Süptitz, F., Catalá, M. M., Piiroinen, J., Oberländer, K. D., Avela, J., & Brüggemann, G.-P. (2011). *Reactive Response and Adaptive Modifications in Dynamic Stability to Changes in Lower Limb Dynamics in the Elderly while Walking BT - 15th Nordic-Baltic Conference on Biomedical Engineering and Medical Physics (NBC 2011)* (K. Dremstrup, S. Rees, & M. Ø. Jensen (Eds.); pp. 268–270). Springer Berlin Heidelberg.

Kaur, R., Sun, R., Ziegelman, L., Sowers, R., & Hernandez, M. (2019). *Using Virtual Reality to Examine the Neural and Physiological Anxiety-Related Responses to Balance-Demanding Target-Reaching Leaning Tasks*. https://doi.org/10.1109/Humanoids43949.2019.9035020

Kennedy, R., Lane, N., Berbaum, K., & Lilienthal, M. (1993). Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, *3*, 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Kodithuwakku Arachchige, S.N.K., Chander, H., Turner, A. J., Wilson, S. J., Simpson, J. D., Knight, A. C., Burch V., R. F., Wade, C., Garner, J. C., & Carruth, D. (2020). Muscle Activity during Postural Stability Tasks: Role of Military Footwear and Load Carriage. *Safety*, *6*(35). https://www.mdpi.com/2313-576X/6/3/35#cite

Kodithuwakku Arachchige, Sachini N K, Chander, H., & Knight, A. (2019). Flatfeet: Biomechanical implications, assessment and management. *The Foot*, *38*, 81–85. https://doi.org/https://doi.org/10.1016/j.foot.2019.02.004

Kodithuwakku Arachchige, Sachini N K, Chander, H., Knight, A. C., Chen, C.-C., Pan, Z., & Turner, A. J. (2020). Impact of foot arch type and minimalist footwear on static postural stability. *Footwear Science*, 1–11. https://doi.org/10.1080/19424280.2020.1791976

Kodithuwakku Arachchige, Sachini N K, Chander, H., Turner, A. J., & Knight, A. C. (2021). Impact of Prolonged Exposure to a Slippery Surface on Postural Stability. In *International Journal of Environmental Research and Public Health* (Vol. 18, Issue 5). https://doi.org/10.3390/ijerph18052214

Landers, M., Wulf, G., Wallmann, H., & Guadagnoli, M. (2005). An external focus of attention attenuates balance impairment in patients with Parkinson's disease who have a fall history. *Physiotherapy*, *91*(3), 152–158. https://doi.org/https://doi.org/10.1016/j.physio.2004.11.010

Lavender, S. A., Polivka, B. J., Darragh, A. R., Sommerich, C. M., Stredney, D. L., & Wills, C. E. (2019). Evaluating Home Healthcare Workers' Safety Hazard Detection Ability Using Virtual Simulation. *Home Healthcare Now*, *37*(5), 265–272. https://doi.org/10.1097/nhh.0000000000000780

Lee, B. C., Kim, C. S., & Seo, K. H. (2019). The Body's Compensatory Responses to Unpredictable Trip and Slip Perturbations Induced by a Programmable Split-Belt Treadmill. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *27*(7), 1389–1396. https://doi.org/10.1109/TNSRE.2019.2921710

Levangie, P. K., & Norkin, C. C. (2011). Gait. In *Joint Structure and Function: A Comprehensive Analysis* (5th ed., pp. 527–530). F. A. Davis Company.

Lin, L., Cockerham, D., Chang, Z., & Natividad, G. (2016). Task Speed and Accuracy Decrease When Multitasking. *Technology, Knowledge and Learning*, *21*. https://doi.org/10.1007/s10758-015-9266-4

Liu, Y.-C., Yang, Y.-R., Tsai, Y.-A., & Wang, R.-Y. (2017). Cognitive and motor dual task gait training improve dual task gait performance after stroke - A randomized controlled pilot trial. *Scientific Reports*, *7*(1), 4070. https://doi.org/10.1038/s41598-017-04165-y

Lohse, K., Sherwood, D., & Healy, A. (2011). Neuromuscular Effects of Shifting the Focus of Attention in a Simple Force Production Task. *Journal of Motor Behavior*, *43*, 173–184. https://doi.org/10.1080/00222895.2011.555436

Maki, B., & McIlroy, W. (2007). Cognitive demands and cortical control of human balance-recovery reactions. *Journal of Neural Transmission (Vienna, Austria : 1996)*, *114*, 1279–1296. https://doi.org/10.1007/s00702-007-0764-y

Marigold, D. S., & Patla, A. E. (2007). Gaze fixation patterns for negotiating complex ground terrain. *Neuroscience*, *144*(1), 302–313. https://doi.org/https://doi.org/10.1016/j.neuroscience.2006.09.006

McIlroy, W. E., & Maki, B. E. (1996). Age-related changes in compensatory stepping in response to unpredictable perturbations. *J Gerontol A Biol Sci Med Sci.*, *51*(6), 289–296.

Mitra, S., Knight, A., & Munn, A. (2013). Divergent effects of cognitive load on quiet stance and task-linked postural coordination. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(2), 323–328. https://doi.org/10.1037/a0030588

National Census of Fatal Occupational Injuries. (2020). https://www.bls.gov/news.release/pdf/cfoi.pdf

Newman, V. E., Liddell, B. J., Beesley, T., & Most, S. B. (2020). Failures of executive function when at a height: Negative height-related appraisals are associated with poor executive function during a virtual height stressor. *Acta Psychologica*, *203*, 102984. https://doi.org/https://doi.org/10.1016/j.actpsy.2019.102984

Norrie, R. G., Maki, B. E., Staines, R. W., & McIlroy, W. E. (2002). The time course of attention shifts following perturbation of upright stance. *Experimental Brain Research*, *146*(3), 315–321. https://doi.org/10.1007/s00221-002-1172-z

Okubo, Y., Brodie, M. A., Sturnieks, D. L., Hicks, C., Carter, H., Toson, B., & Lord, S. R. (2018). Exposure to trips and slips with increasing unpredictability while walking can improve balance recovery responses with minimum predictive gait alterations. *PLOS ONE*, *13*(9), e0202913. https://doi.org/10.1371/journal.pone.0202913

Pan, T., Wang, H., Si, H., Li, Y., & Shang, L. (2021). Identification of pilots' fatigue status based on electrocardiogram signals. *Sensors*, *21*(9), 3003. https://doi.org/10.3390/s21093003

Paran, I., Nachmani, H., & Melzer, I. (2020). A concurrent attention-demanding task did not interfere with balance recovery function in standing and walking among young adults – An explorative laboratory study. *Human Movement Science*, *73*(September), 102675. https://doi.org/10.1016/j.humov.2020.102675

Park, K., Rosengren, K. S., Horn, G. P., Smith, D. L., & Hsiao-Wecksler, E. T. (2011). Assessing gait changes in firefighters due to fatigue and protective clothing. *Safety Science*, *49*(5), 719–726. https://doi.org/10.1016/j.ssci.2011.01.012

Patel, P. J., & Bhatt, T. (2015). Attentional demands of perturbation evoked compensatory stepping responses: Examining cognitive-motor interference to large magnitude forward perturbations. *Journal of Motor Behavior*, *47*(3), 201–210. https://doi.org/10.1080/00222895.2014.971700

Pater, M. L., Rosenblatt, N. J., & Grabiner, M. D. (2015). Expectation of an upcoming large postural perturbation influences the recovery stepping response and outcome. *Gait & Posture*, *41*(1), 335–337. https://doi.org/10.1016/j.gaitpost.2014.10.026

Peterka, R. J. (2002). Sensorimotor integration in human postural control. *Journal of Neurophysiology*, *88*(3), 1097. http://jn.physiology.org/content/88/3/1097.abstract

Peterson, S., Furuichi, E., & Ferris, D. (2018). Effects of virtual reality high heights exposure during beam-walking on physiological stress and cognitive loading. *PLOS ONE*, *13*, e0200306. https://doi.org/10.1371/journal.pone.0200306

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2001). Changes in walking pattern caused by the possibility of a tripping reaction. *Gait & Posture*, *14*(1), 11–18. https://doi.org/https://doi.org/10.1016/S0966-6362(01)00110-2

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2004). Contribution of the support limb in control of angular momentum after tripping. *Journal of Biomechanics*, *37*(12), 1811–1818. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.02.038

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2005). How early reactions in the support limb contribute to balance recovery after tripping. *Journal of Biomechanics*, *38*(3), 627–634. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.03.029

Pijnappels, M., Bobbert, M., & Van Dieen, J. (2005). Control of Support Limb Muscles in Recovery after Tripping in Young and Older Subjects. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *160*, 326–333. https://doi.org/10.1007/s00221-004-2014-y

Pimentel, G., Rodrigues, S., Silva, P. A., Vilarinho, A., Vaz, R., & Silva Cunha, J. P. (2019). A wearable approach for intraoperative physiological stress monitoring of multiple cooperative surgeons. *International Journal of Medical Informatics*, *129*(May 2018), 60–68. https://doi.org/10.1016/j.ijmedinf.2019.05.028

Potocanac, Z., & Duysens, J. (2017). Online adjustments of leg movements in healthy young and old. *Experimental Brain Research*, *235*, 1–20. https://doi.org/10.1007/s00221-017-4967-7

Qu, X., Xie, Y., Hu, X., & Zhang, H. (2020). Effects of Fatigue on Balance Recovery From Unexpected Trips. *Human Factors*, *62*(6), 919–927. https://doi.org/10.1177/0018720819858794

Rankin, J. K., Woollacott, M. H., Shumway-Cook, A., & Brown, L. A. (2000). Cognitive influence on postural stability: A neuromuscular analysis in young and older adults. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences*, *55*(3), 112–119. https://doi.org/10.1093/gerona/55.3.M112

Rashedi, E., Songra, R., Lockhart, T., & Nussbaum, M. (2016, August). Effects of Plantarflexor Muscle Fatigue on Gait Characteristics. *40th Annual Meeting of the American Society of Biomechanics*.

Redfern, M. S., & DiPasquale, J. (1997). Biomechanics of descending ramps. *Gait and Posture*, *6*(2), 119–125. https://doi.org/10.1016/S0966-6362(97)01117-X

Renga, V. (2019). Clinical Evaluation of Patients with Vestibular Dysfunction. *Neurology Research International*, *2019*, 3931548. https://doi.org/10.1155/2019/3931548

Rhea, C. K., & Rietdyk, S. (2011). Influence of an unexpected perturbation on adaptive gait behavior. *Gait and Posture*, *34*(3), 439–441. https://doi.org/10.1016/j.gaitpost.2011.06.011

Rodgers, M., & Cavanagh, P. (1984). Glossary of biomechanical terms, concepts, and units. *Physical Therapy*, *64*(12), 1886–1902.

Salassa, J., & Zapala, D. (2009). Love and Fear of Heights: The Pathophysiology and Psychology of Height Imbalance. *Wilderness & Environmental Medicine*, *20*, 378–382. https://doi.org/10.1580/1080-6032-020.004.0378

Sasagawa, S., Shinya, M., & Nakazawa, K. (2013). Interjoint dynamic interaction during constrained human quiet standing examined by induced acceleration analysis. *Journal of Neurophysiology*, *111*(2), 313–322. https://doi.org/10.1152/jn.01082.2012

Schillings, A. M., Van Wezel, B. M. H., & Duysens, J. (1996). Mechanically induced stumbling during human treadmill walking. *Journal of Neuroscience Methods*, *67*(1), 11–17. https://doi.org/10.1016/0165-0270(95)00149-2

Schillings, A. M., Van Wezel, B. M. H., Mulder, T., & Duysens, J. (2000). Muscular responses and movement strategies during stumbling over obstacles. *Journal of Neurophysiology*, *83*(4), 2093–2102. https://doi.org/10.1152/jn.2000.83.4.2093

Shendarkar, A., Vasudevan, K., Lee, S., & Son, Y.-J. (2008). Crowd simulation for emergency response using BDI agents based on immersive virtual reality. *Simulation Modelling Practice and Theory*, *16*(9), 1415–1429. https://doi.org/https://doi.org/10.1016/j.simpat.2008.07.004

Shimada, H., Obuchi, S., Furuna, T., & Suzuki, T. (2004). New Intervention Program for Preventing Falls Among Frail Elderly People: The Effects of Perturbed Walking Exercise Using a Bilateral Separated Treadmill. *American Journal of Physical Medicine & Rehabilitation*, *83*(7). https://journals.lww.com/ajpmr/Fulltext/2004/07000/New_Intervention_Program_for_Preventing_Falls.1.aspx

Shumway-Cook, A., & Woollacott, M. (2000). Attentional demands and postural control: the effect of sensorycontext. *The Journals of Gerontology: Series A*, *55*(1), M10–M16. https://doi.org/10.1093/gerona/55.1.M10

Shumway-Cook, Anne, & Horak, F. B. (1986). Assessing the influence of sensory interaction on balance suggestion from the field. *Physical Therapy*, *66*(10), 1548–1550. https://doi.org/10.1093/ptj/66.10.1548

Silver, T. A., Mokha, G. M., & Peacock, C. A. (2016). Exploring fall training adaptations while walking. *Work*, *54*(3), 699–707. https://doi.org/10.3233/WOR-162321

Simeonov, P. I., Hsiao, H., DotsonM, B. W., & Ammons, D. E. (2005). Height Effects in Real and Virtual Environments. *Human Factors*, *47*(2), 430–438. https://doi.org/10.1518/0018720054679506

Smeesters, C., Hayes, W. C., & McMahon, T. A. (2001). The threshold trip duration for which recovery is no longer possible is associated with strength and reaction time. *Journal of Biomechanics, 34*(5), 589–595. https://doi.org/https://doi.org/10.1016/S0021-9290(01)00005-7

Taube, W., Schubert, M., Gruber, M., Beck, S., Faist, M., & Gollhofer, A. (2006). Direct corticospinal pathways contribute to neuromuscular control of perturbed stance. *Journal of Applied Physiology, 101*(2), 420. http://jap.physiology.org/content/101/2/420.abstract

Troy, K., & Grabiner, M. (2005). The presence of an obstacle influences the stepping response during induced trips and surrogate tasks. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *161*, 343–350. https://doi.org/10.1007/s00221-004-2078-8

United States Department of Labor, Bureau of Labor Statistics, Census of Fatal Occupational Injuries . (2014).

Walsh, G. S. (2021). Visuomotor control dynamics of quiet standing under single and dual task conditions in younger and older adults. *Neuroscience Letters*, *761*(February), 136122. https://doi.org/10.1016/j.neulet.2021.136122

Wang, H., Wang, Q., & Hu, F. (2019). Are you afraid of heights and suitable for working at height? *Biomedical Signal Processing and Control*, *52*, 23–31. https://doi.org/https://doi.org/10.1016/j.bspc.2019.03.011

Wang, Q., Wang, H., & Hu, F. (2018). Combining EEG and VR Technology to Assess Fear of Heights. *2018 9th International Conference on Information Technology in Medicine and Education (ITME)*, 110–114. https://doi.org/10.1109/ITME.2018.00034

Wang, T.-Y., Bhatt, T., Yang, F., & Pai, Y.-C. (2012). Adaptive control reduces trip-induced forward gait instability among young adults. *Journal of Biomechanics*, *45*(7), 1169–1175. https://doi.org/https://doi.org/10.1016/j.jbiomech.2012.02.001

Wang, Y., Wang, S., Bolton, R., Kaur, T., & Bhatt, T. (2019). Effects of task - specific obstacle - induced trip - perturbation training : proactive and reactive adaptation to reduce fall - risk in community - dwelling older adults. *Aging Clinical and Experimental Research*, *0123456789*. https://doi.org/10.1007/s40520-019-01268-6

Weerdesteyn, V., Schillings, A. M., Duysens, J., & Van Galen, G. P. (2003). Distraction Affects the Performance of Obstacle Avoidance During Walking. *Journal of Motor Behavior*, *35*(1), 53–63. https://doi.org/10.1080/00222890309602121

Wickens, C. (1981). *Processing Resources in Attention, Dual Task Performance, and Workload Assessment.* Taler & Francis.

Winter, D. A. (1991). *The biomechanics and motor control of human gait : normal, elderly and pathological* (2nd ed.). Waterloo Biomechanics. https://trid.trb.org/view/770965

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, *3*(4), 193–214. https://doi.org/10.1016/0966-6362(96)82849-9

Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement*. https://books.google.com/books?id=_bFHL08IWfwC

Winter, David A, Patla, A. E., Prince, F., Ishac, M., & Gielo-Perczak, K. (1998). Stiffness Control of Balance in Quiet Standing. *Journal of Neurophysiology*, *80*(3), 1211. http://jn.physiology.org/content/80/3/1211.abstract

Witmer, B., & Singer, M. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence Teleoperators &amp Virtual Environments*, *7*. https://doi.org/10.1162/105474698565686

Wong, W. L., Masters, R. S. W., Maxwell, J. P., & Abernethy, A. B. (2007). Reinvestment and Falls in Community-Dwelling Older Adults. *Neurorehabilitation and Neural Repair*, *22*(4), 410–414. https://doi.org/10.1177/1545968307313510

Wulf, G, & Lewthwaite, R. (2016). Optimizing performance through intrinsic motivation and attention for learning: The OPTIMAL theory of motor learning. *Psychonomic Bulletin & Review*, *23*. https://doi.org/10.3758/s13423-015-0999-9

Wulf, Gabriele, McNevin, N., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology Section A*, *54*(4), 1143–1154. https://doi.org/10.1080/713756012

Wulf, Gabriele, Weigelt, M., Poulter, D., & McNevin, N. (2003). Attentional focus on suprapostural tasks affects balance learning. *THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY*, *57A*(7), 1191–1211. http://journals.sagepub.com/doi/pdf/10.1080/02724980343000062

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders : Official Journal of the Movement Disorder Society*, *23*(3), 329–472. https://doi.org/10.1002/mds.21720

Yu, W., Cha, S., & Seo, S. (2017). The effect of ball exercise on the balance ability of young adults. *Journal of Physical Therapy Science*, *29*(12), 2087–2089. https://doi.org/10.1589/jpts.29.2087

Zaback, M., Adkin, A. L., & Carpenter, M. G. (2019). Adaptation of emotional state and standing balance parameters following repeated exposure to height-induced postural threat. *Scientific Reports*, *9*(1), 1–13. https://doi.org/10.1038/s41598-019-48722-z

CHAPTER III

MANUSCRIPT I: ANKLE JOINT KINEMATICS IN EXPECTED AND UNEXPECTED TRIP RESPONSES WITH DUAL-TASKING AND PHYSICAL FATIGUE

Introduction

In the year 2019, a total of 880 fatal occupational injuries, which were attributed to 16.5% of all occupational deaths, occurred due to slips, trips, and falls (STFs) (*Bureau of Labor Statistics*, 2020). This number of deaths was an 11% increase compared to the occupational deaths in 2018 (*National Census of Fatal Occupational Injuries*, 2020). Moreover, 244,000 nonfatal injuries were reported in the private industry due to STFs, causing 8.7% of all occupational injuries in 2019 (*BLS*, 2020). STFs are frequently observed among the occupational categories such as construction workers, manufacturers, roofers, carpenters, tree trimmers, miners, and agricultural workers (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor.* 2017). Such nonfatal injuries could cause dreadful outcomes, such as spinal cord and head injuries, which potentially cause long-term or permanent disabilities (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor*, 2017). Thus, STFs affect the workers' health, quality of life, productivity, and earning capacity. In addition, since fall-related outcomes decrease the worker effectiveness, the productivity of the entire workplace gets affected, causing financial losses to the employer. Furthermore, medical bills, worker compensations, and hiring replacement workers add to the economic burden of the workplace. Approximately $70 billion is spent on occupational falls in the United States of America annually (*United States Department of Labor, BLS, Census of Fatal Occupational Injuries*, 2014). Hence, minimizing falls in the ergonomic settings is mandatory, and it will benefit both employees as well as the employer.

Trips are widely prevalent at workplaces due to the abundance of trip hazards like steps, rugs, cords, equipment, and tools (*BLS*, 2020). Further, the tasks and environmental conditions in the ergonomic settings, such as load carrying, poor lighting, and cluttered environments, increase the possibility of trips among the workers (Silver et al., 2016). Divided attention, cognitive/motor fatigue, lack of anticipation, and inexperience are causes of frequent trips and unsatisfactory trip recovery (Inkol et al., 2018; Paran et al., 2020; Weerdesteyn et al., 2003). Trips occur due to inefficient toe clearance during obstacle crossing or direct contact of the foot with an obstacle (Eng et al., 1994). Following a trip, the body undergoes a perturbation in all three dimensions, but the movements in the sagittal plane are more prominent (Burg et al., 2005). These sagittal plane joint kinematics are vitally important in clearing obstacles to avoid a trip. Immediately after a trip, the upper body undergoes a forward moment, which can be successfully counteracted if the recovery foot is placed anterior to the COM (Pijnappels, Bobbert, & van Dieën, 2005). Thus, stepping kinematics are crucial to regain postural stability upon tripping. Lower extremity joint kinematics are usually used to quantify the intensity and effectiveness of balance recovery upon postural perturbations (Franz et al., 2017). Usually, the ankle joint undergoes dorsiflexion during the trip and later undergoes plantar flexion to place the recovery foot anterior to the body's Center of Mass (COM) to regain stability (Eng et al., 1994; Pijnappels et al., 2001; Pijnappels, Bobbert, & Van Dieen, 2005). Eng et al. (1994) introduced two main behavioral strategies for the tripping leg; lowering-hit and elevating-hit strategies. In the lowering-hit strategy, the tripping foot contacts the obstacle and is promptly lowered to the surface and placed posterior to the obstacle. In this strategy, the recovery step (the immediate step after the trip) is taken by the non-tripping foot. In the elevating-hit strategy, the tripping foot contacts the obstacle and is placed anterior to the obstacle; thus, the same tripping foot is used to take the recovery step.

Distraction and lack of anticipation of a trip hazard are significant causes of trip-induced falls (Elfering et al., 2018). Although the reactive responses to a perturbation are extremely decisive in the trip outcome, the proactive mechanisms also play a mandatory role (Wang et al., 2019). The reactive responses occur following the contact with the obstacle to correct the posture in a feedback loop, while proactive responses occur before contacting an obstacle (with the anticipation of a trip) as a feedforward mechanism. However, the studies that compare expected and unexpected trip perturbations are rare in the previous literature. Pater and coworkers (2015) assessed the fall rate, trip-recovery kinematics, and reaction time during expected and unexpected treadmill-based perturbations in a group of older women (age 64 ± 7.1 years). The researchers observed that during expected perturbations, the participants had a lesser fall rate and better trip recovery kinematics (smaller trunk flexion angle, reduced trunk velocity) (Pater et al., 2015).

Over the previous years, dual tasking and multi-tasking have been used to assess attention and its effects on postural control (Abuin-Porras et al., 2018). The simultaneous performance of two tasks is known as dual tasking (DT) (Wickens, 1981), while the simultaneous performance of three tasks can be considered triple tasking (TT). These simultaneous tasks could be motor (physical), cognitive (mental), or a combination of motor and cognitive tasks. In contrast to single-tasking (ST), DT and TT require attention switching between the tasks; thus, the performance accuracy is usually affected in DT and TT (Lin et al., 2016). Performing a concurrent task while walking (e.g., carrying a load) is often observed in ergonomic settings due to its associated benefits (e.g., achieving more tasks within a short time). Although gait was previously viewed as a semi-automatic process, it is currently considered a process that requires a significant allocation of attentional resources (Bloem et al., 2001). Therefore, an added secondary task during gait (i.e., DT) could hinder both activities due to divided attention. Besides the failures in achieving tasks successfully, DT or TT usually does not cause detrimental effects during normal day-to-day activities. However, the ergonomic population performs mentally and physically demanding tasks constantly. Hence, a minimal performance decrement in either task could cause catastrophic outcomes in such populations. Therefore, the ergonomic population must be trained in performing DT/TT under various circumstances (e.g., poor lighting conditions, rain). In addition, cognitive and physical fatigue is highly prevalent in occupational settings. Due to high work demands, long working hours, inadequate rest, and unfavorable environmental conditions, physical fatigue is inevitable among the workers (Dong, 2005). Physical fatigue affects postural control, including gait, trip incidence, trip severity, and trip recovery leading to falls (Barbieri et al., 2014; Kodithuwakku Arachchige et al., 2020; Kodithuwakku Arachchige et al., 2021; Park et al., 2011). Therefore, preventing undue fatigue is crucial to minimize its negative effects on the workers.

Although the biomechanics of slips and slip recovery has been studied to a certain extent thus far, there is still a dearth of literature on trip biomechanics. More specifically, there is a significant lack of understanding of the lower extremity joint kinematics during trip response. In addition, the number of trip-related studies conducted on the healthy young population is minimal. However, the majority of construction, manufacturing, and roofing employees are young, healthy adults (*Employed Persons by Detailed Industry and Age*, 2020). Hence, more trip-related research is warranted among the young, healthy population, which could be applied to the novice occupational population. Therefore, the purpose of this study was to investigate the ankle joint kinematics in unexpected and expected trip responses during ST, DT, and TT, before and after a physically fatiguing exercise among young, healthy adults. It was hypothesized that the ankle kinematics would be significantly different between UT, ET, and NG, before and after physical fatigue, as well as during ST, CDT, MDT, and TT.

Methodology

Participants

Twenty collegiate volunteers (10 females, one left leg dominant, age 20.35 ± 1.04 years, height 174.83 ± 9.03 cm, mass 73.88 ± 15.55 kg) with no history of musculoskeletal, neurological, visual, and vestibular abnormalities were recruited for the study. Only recreationally active individuals [a minimum of aerobic exercises 3-4 days/ week or 150min/ week and resistance training two days/week for the last three months- ACSM guidelines (Ferguson, 2014)] were included in the study.

Study Design

The study was approved by the university Institutional Review Board (IRB # 21-416). The experiment followed a repeated measures design with a counterbalanced task assignment. As a baseline measurement, data from the unperturbed gait (normal gait; NG) was collected first, followed by unexpected trip (UT) and expected trip (ET) during single-tasking (ST), cognitive dual tasking (CDT), motor dual-tasking (MDT), and triple tasking (TT), before (PRE) and after (POST) physically fatiguing exercise.

Instrumentation

The participants' gait kinematics were recorded with a 3-dimensional (3D) motion capture system (Motion Analysis Corporation, Santa Rosa, CA) at a sampling rate of 100 Hz. The participants performed gait trials on a Gaitway biomechanics treadmill with railings removed (H/P/cosmos® Kistler, Switzerland). In order to prevent fall-related injuries, the participants wore a back-pack type fall-arrest harness (Protecta PRO harness). A 360 GoPro fusion camera captured certain construction site pictures to be used for the CDT (Shojaei et al., 2020). Borg's ratings of perceived exertion (RPE) scale was used to assess subjective physical fatigue in the participants.

Experimental Procedures

The testing consisted of two days: a familiarization day and a test day. On the familiarization day, obtaining informed consent, completing a Physical Activity Readiness Questionnaire (PARQ) to identify any existing risk factors, and collecting demographic (age, gender), and collecting anthropometric data (height, mass) were done. Participants' functional leg dominance was determined using the ball-kick, step-up, and balance recovery tests (Lin et al., 2009). Since this study involves a task of identifying occupational hazards, the participants were familiarized with different occupational hazards they might observe on the television screen during testing. Then, they were familiarized with the fall arrest harness, and the harness rope length was measured to have at least 10 cm from the ground to their knee joint (when the entire body weight was put on the harness, with both feet off the ground) to avoid contact injuries following a loss of balance (Okubo et al., 2019). After noting down the required harness length, the participants were familiarized with treadmill walking for 2 minutes (Aaslund et al., 2011). However, during familiarization, no practice perturbations were administered in order to avoid learning effects (Lee et al., 2019). Upon completion of the familiarization session, the subjects were scheduled for testing and were advised to refrain from any vigorous physical activity/workouts on the day before the testing day.

Once the participants arrived on the test day, reflective motion capture markers were attached bilaterally in a full-body Helen-Hayes model. After preparation, the participants were directed to the treadmill, attached to the fall-arrest harness, the rope length was adjusted, and asked to walk at a self-selected pace (average walking speed 2.71 ± 0.74 mph). As the participants walked, their lower extremity joint kinematics were recorded during normal gait (NG) to be used as a baseline reading. Upon recording the NG trial, a trip perturbation was induced without any warning (unexpected trip; UT), followed by a trip perturbation after a countdown of "3, 2, 1" (expected trip; ET). These three trials (NG, UT, ET) were recorded when the participants were only walking (single-tasking, ST) and were always performed before administering DT or TT tasks. The same researcher induced the trip perturbations manually (Okubo et al., 2019) with a sandbag thrown onto the treadmill belt. The participants' anterior visual field was blocked using a table, and they were asked to wear dribbling goggles to block the inferior visual field (Figure 1, left). Thus, the participants were not able to see the trip induction. All participants were tripped on their dominant leg during mid-swing (Okubo et al., 2019; Pijnappels et al., 2004). Participants were not provided with specific directions on regaining balance upon tripping, except "try to recover your balance if you trip." After ST, the participants were advised to perform cognitive DT (CDT), motor DT (MDT), and TT in a randomized order to avoid learning effects (Lee et al., 2019). As the cognitive DT, they identified occupational hazards in a picture displayed on a television (Figure 1, middle). As the motor DT, they carried an anterior load, which was 10% of their body weight (Figure 1, left)

(Kim & Lockhart, 2008). In TT, the participants identified occupational safety hazards on a picture displayed on the television while carrying the anterior load. NG, UT, and ET trials were recorded in the same order (i.e., NG followed by UT, followed by ET) for every CDT, MDT, and TT task. Thus, there were a total of four trials without perturbations (ST, CDT, MDT, TT), four trials of UT (ST, CDT, MDT, TT), and four trials of ET (ST, CDT, MDT, TT). Upon completing these 12 trials, the participants completed a physically fatiguing protocol that included repeated stand-to-sit exercises (Qu et al., 2020). For this protocol, one repetition included standing on a 20 cm high bench and then getting off the bench at a rate of 40 Hz (Figure 1, right) (Qu et al., 2020). As Borg's RPE is highly related to high-intensity, short-term physical fatigue (Ratel et al., 2006), it was used to assess the subjective fatigue level. At every 10 seconds during the fatiguing protocol, the participants were asked to rate their fatigue level using Borg's RPE, and once they exceeded "17" on the scale, they were considered very fatigued (average time to fatigue 4.24 ± 1. 76 minutes) (Qu et al., 2020). After inducing fatigue in the participants, the same 12 trials that were done before fatigue was repeated. During every trip trial, the participant's trip recovery strategy (lowering-hit, elevating-hit) was noted. In addition, to understand the participants' subjective trip anticipation, immediately following each UT, they were asked "on a scale from 0-10, with 0 being the most expected and 10 being the most unexpected, please rate the trip you just experienced".

Figure 4

Participants performing the motor dual-task (left), cognitive dual-task (middle), and the physically fatiguing exercise (right).

Data Acquisition

The raw data from the 3D motion capture system were cleaned by removing unlabeled markers, the gaps were filled, and filtered using a 30 Hz Butterworth filter. The dominant leg toe marker was used to determine the trip initiation in UT and ET. All trip trials were trimmed from the initiation of the trip to the next heel strike of the dominant leg. Sagittal plane maximum and minimum ankle angles were determined upon exporting joint kinematics data to excel sheets. These ankle kinematic data during UT and ET were compared with the corresponding kinematic data during unperturbed gait (NG).

Data Analysis

Both maximum and minimum ankle angles were individually analyzed using a 2 (time; PRE, POST) x 4 (tasks; ST, CDT, MDT, TT) x 3 (gait; NG, UT, ET) repeated measures factorial analysis of variance (ANOVA). Mauchly's test of sphericity was determined to see if the assumption of sphericity was met. Any main effect significant differences in time, task, and gait trials were further analyzed using Bonferroni post-hoc comparisons. For all analyses, the alpha level was set at an apriori 0.05, and all analyses were performed using the SPSS 27 statistical software package.

Results

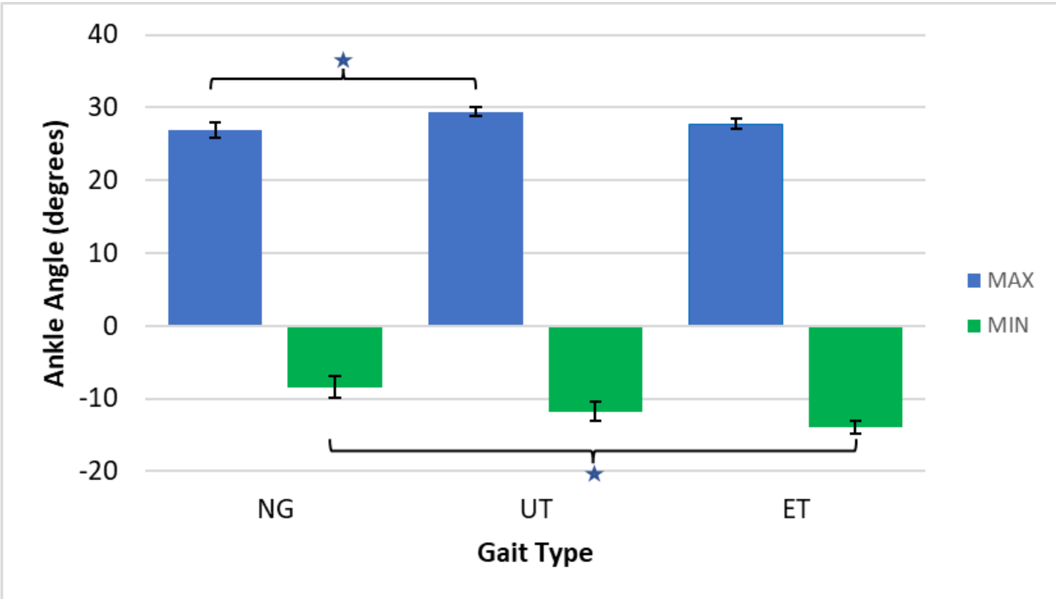
The repeated measures factorial ANOVA revealed significant main effects of task and gait trials when considering maximum ankle joint angle and significant main effects of time and gait trials when considering minimum ankle joint angle. A significant gait main effect was observed in maximum ankle angle (F (2, 38) = 4.48; p = .018; ηp^2 = 0.19). Post-hoc analysis using Bonferroni corrections revealed significant differences between NG and UT trials (p = .026), with a greater maximum ankle angle during UT compared to NG (Figure 2). Moreover, a significant gait main effect was observed in minimum ankle angle (F (2, 38) = 8.20; p = .001; ηp^2 = 0.30). Post-hoc analysis using Bonferroni corrections revealed significant differences between NG and ET trials (p = .006), with a greater minimum ankle angle during ET compared to NG (Figure 2).

A significant task main effect was observed in maximum ankle angle (F (3, 57) = 9.32; p < 0.001; ηp^2 = 0.33). Post-hoc analysis using Bonferroni corrections revealed significant differences between ST and MDT (p = .013), with a greater maximum ankle angle during MDT compared to ST. In addition, the post-hoc comparisons revealed significant differences between

ST and TT (p = .002), with a greater maximum ankle angle during TT compared to ST (Figure 3). However, no significant task main effects were observed in minimum ankle angles.

Figure 5

Maximum and minimum ankle angles during different gait types.

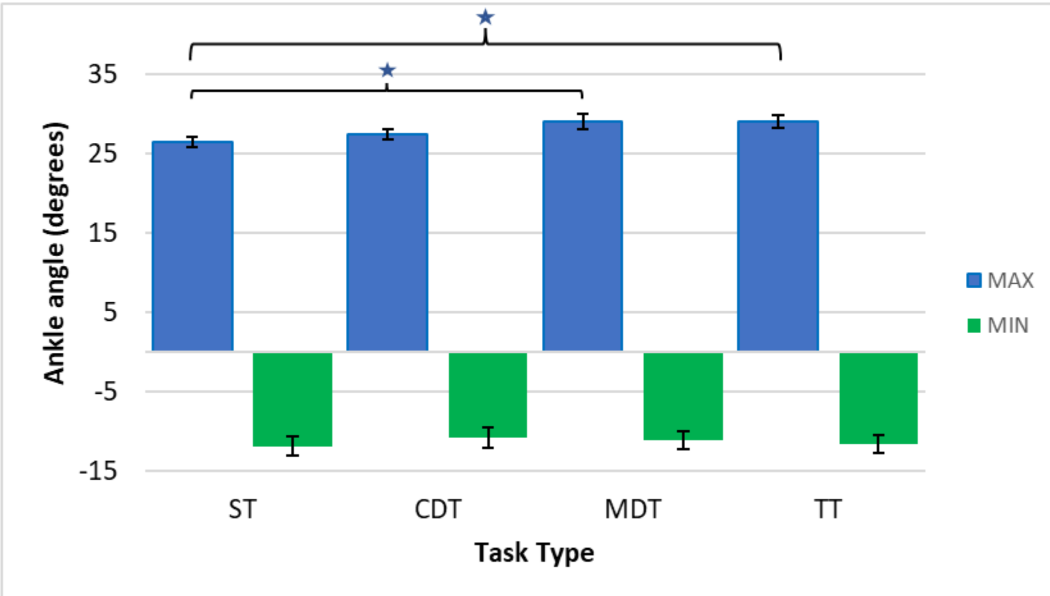


Blue columns represent maximum ankle angles, and the green columns represent minimum ankle angles. NG: normal (unperturbed) gait; UT: unexpected trip; ET: expected trip. ★ represent significant gait type differences. Bars represent the standard error.

There were no time main effects observed in maximum ankle angles. However, there was a significant time main effect was observed in minimum ankle angle (F (1, 19) = 10.20; p = 0.005; ηp^2 = 0.35) with greater minimum angles during post-fatigue compared to pre-fatigue.

Figure 6

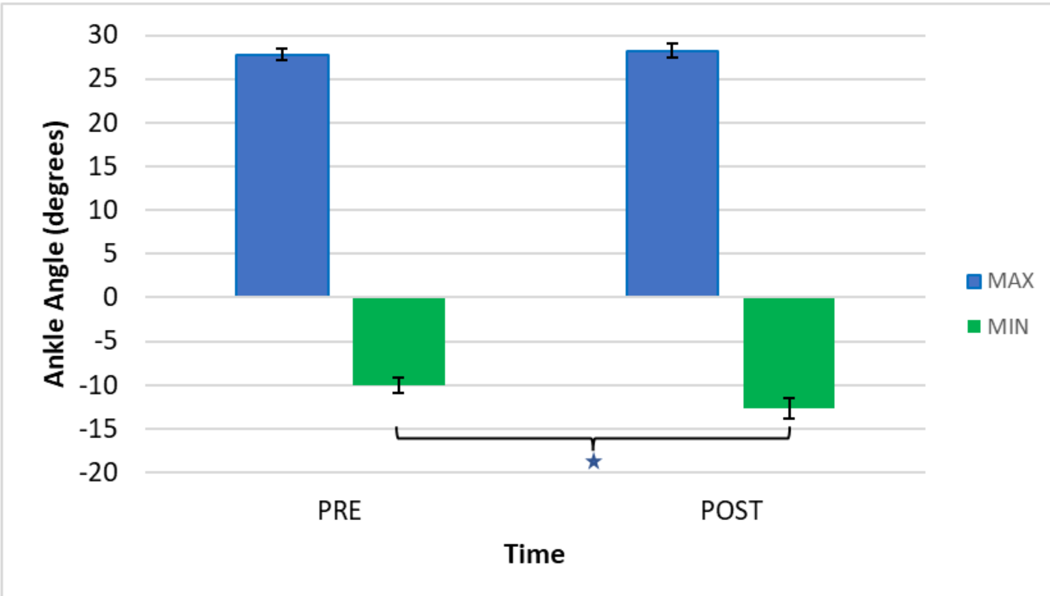
Maximum and minimum ankle angles during different tasks.



Blue columns represent maximum ankle angles, and the green columns represent minimum ankle angles. ST: single-tasking; CDT: cognitive dual-task; MDT: motor dual-task; TT: triple task. ★ represent significant task differences. Bars represent the standard error.

Figure 7

Maximum and minimum ankle angles before and after physical fatigue.



Blue columns represent maximum ankle angles, and the green columns represent minimum ankle angles. PRE: before physical fatigue; POST: after physical fatigue. ★ represent significant time differences. Bars represent the standard error.

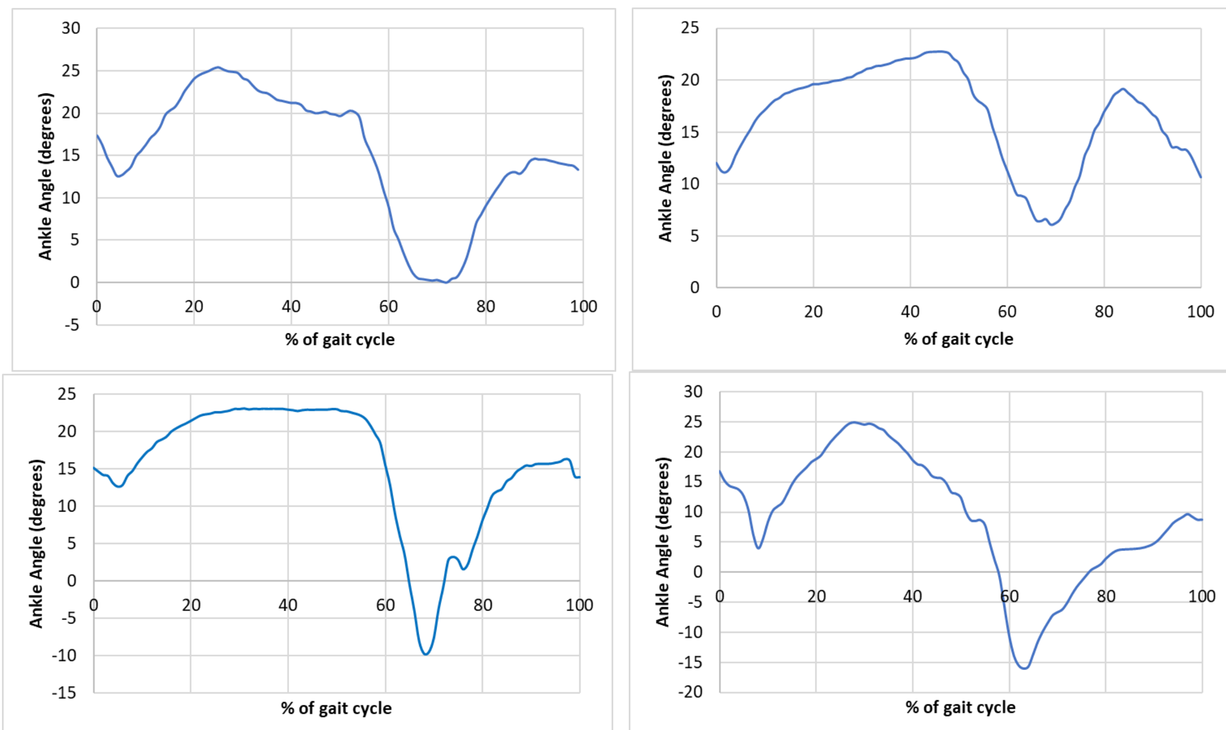
There was a significant time x task x gait interaction (*F* (6, 114) = 6.08; $p < 0.001$; $\eta p^2 = 0.24$) observed in maximum ankle angles. In addition, there were significant time x task (*F* (3, 57) = 11.22; $p < 0.001$; $\eta p^2 = 0.37$), task x gait (*F* (6, 114) = 4.38; $p < 0.001$; $\eta p^2 = 0.19$), and time x task x gait (*F* (6, 114) = 3.15; $p = 0.007$; $\eta p^2 = 0.14$) observed in minimum ankle angles. During 86.96% of the unexpected trip trials, the participants acquired the lowering-hit strategy, and during 82.67% of the expected trips, participants acquired the lowering-hit strategy. Figure 5 demonstrates ankle kinematic trajectories of the tripping leg while performing lowering-hit and elevating-hit strategies during UT and ET trials from a single subject.

Participants' subjective trip anticipation was assessed following all eight unexpected trips on a scale from 0-10, with 0 being the most expected and 10 being the most unexpected.

According to the participants' ratings, the 5th trip was the most expected, while the 7th trip was the most unexpected (Table 1). If both feet of the participant came off the treadmill during a trip trial, it was planned to consider as a fall. However, none of the participants fell during the trip perturbations.

Figure 8

Tripping leg ankle kinematic trajectories from a single subject during unexpected and expected trip trials.



Top left: unexpected trip, lowering-hit strategy; Top right: unexpected trip, elevating-hit strategy; Bottom left: expected trip, lowering-hit strategy; Bottom right: expected trip, elevating-hit strategy. Positive angles indicate dorsiflexion (DF), and the negative angles indicate plantarflexion (PF).

Table 1

Participants' subjective anticipation of trips over the eight unexpected trip trails.

UT trial number	Mean anticipation rating ± standard deviation
1	6.65 ± 2.46
2	7.16 ± 1.57
3	7.39 ± 1.65
4	7.17 ± 1.69
5	6.63 ± 1.95
6	7.44 ± 1.76
7	7.75 ± 1.77
8	7.44 ± 1.63

Discussion

The purpose of this study was to investigate the ankle joint kinematics in unexpected and expected trip responses during ST, DT, and TT, before and after a physically fatiguing exercise in a young, healthy population. It was hypothesized that the ankle kinematics would be significantly different between UT, ET, and NG, before and after physical fatigue, as well as during ST, CDT, MDT, and TT. The findings of this study revealed significant differences in maximum ankle angle between ST and UT, ST and ET, NG and UT, as well as a significant interaction between time x task x gait. More specifically, a greater maximum ankle angle was observed during UT compared to NG, MDT compared to ST, and TT compared to ST. Moreover, significant differences in minimum ankle angle were observed between NG and ET as well as before (PRE) and after (POST) physical fatigue. Particularly, a greater minimum ankle angle was observed during ET compared to NG and during post-fatigue (POST) compared to pre-fatigue (PRE). In addition to the main effects, significant time x task, task x gait, and time x task x gait interactions were observed.

Ankle joint kinematics during NG, UT, and ET

According to the results of this study, compared to the unperturbed gait (NG), the participants have demonstrated greater DF during the response for UT and greater PF during the response for ET. These significant differences in maximum and minimum ankle angles during UT and ET compared to NG indicates a significant difference between actual and perceived sensory feedback, which potentially led the participants to acquire a recovery model unique to each trip type. These ankle kinematic trends observed in the present study are in line with the previous studies, such as Eng et al. (1994) and King et al. (2019).

Upon contacting a trip hazard, the individual's upper body undergoes a sudden forward (negative) moment, shifting the center of gravity (COG) anteriorly. This forward moment, COG shift, and suddenly acquired unilateral stance significantly threaten the individual's postural control. The COG could shift outside the base of support (BOS) with larger perturbations, which must be promptly realigned back within the BOS to maintain postural stability. Thus, the ankle angle differences during UT and ET trials can be attributed to the occurrence of the trip followed by the balance recovery response acquired to regain balance. During walking, DF is important to clear the obstacle; therefore, it could be assumed that the participants attempted to maintain a greater DF angle during UT in order to clear the obstacle. As the individuals land from a trip, a slight PF is usually observed to promptly contact the ground and regain balance (Pijnappels et al., 2008). The participants of this study demonstrated greater PF during ET, which could be viewed as an anticipatory adjustment. During ET, the participants were tripped following a countdown of 3, 2, 1; thus, they must have made an adjustment for successful trip recovery by increasing PF.

Although it was expected to observe significant differences in ankle angle between UT and ET, it was not evident in this study. The impact of anticipation of a postural perturbation on gait kinematics has been controversial in the previous literature. While some researchers have shown kinematic gait adaptations with an anticipation of an impending trip (Wang et al., 2012), some researchers have shown no significant adaptations in the joint kinematics with anticipation (Pijnappels et al., 2001). In the present study, the participants were aware that they would be tripped during some gait trials. Although the authors made every attempt to prevent anticipation of a trip, and the subjective trip anticipation rating (Table 1) indicated otherwise, the participants might have anticipated when a UT was about to happen. Hence, they could have had created a recovery response created, which could be the reason for insignificant differences between UT and ET ankle angles.

Ankle joint kinematics during ST, CDT, MDT, and TT

In this study, compared to ST, the participants acquired greater DF during the trip response while performing MDT and TT. Both gait and trip recovery were formerly thought of as a fully reflex-driven process requiring minimal attention. However, this concept has been disregarded with the developments during the past few decades, upon understanding the significantly increased prefrontal cortex activity during postural control, which indicates attentional processing (Maki & McIlroy, 2007; Yogev-Seligmann et al., 2008). During postural control, simultaneous cognitive or motor tasks cause divided attention, leading to a trade-off between the primary and the secondary tasks (Wickens, 1981). Thus, DT could alter the trip occurrence and severity due to the limited attention capacity, which probably has manifested by the altered ankle joint kinematics.

However, no significant differences in trip recovery responses were observed between ST and CDT. Both cognitive task and trip recovery demand a significant amount of cognitive involvement. Therefore, it can be assumed that the participants have acquired the “posture-first strategy” during CDT, where they prioritize postural control over the cognitive task. A similar finding was observed by Inkol et al. (2018), who investigated balance recovery responses during support surface translations with and without CDT using an auditory Stroop test. The authors did not observe any significant differences in the recovery parameters between CDT and ST, but the response time for the auditory Stroop test was longer during CDT. Therefore, the authors mentioned that their study supports the “posture-first strategy” (Inkol et al., 2018). Similarly, in another study, in which the authors included a CDT with a visuomotor tracking task, they observed a pause in the cognitive task immediately after the postural perturbations, indicating the “posture-first strategy” (Norrie et al., 2002). However, this finding was not persisted during TT, where significant differences were observed compared to ST. In this study, during TT, the participants carried an anterior load and performed a cognitive task while recovering from trip perturbations simultaneously. The attentional requirement for a particular task depends on many factors, including the task/s at hand. Less attentional resources are needed for simpler tasks, while more attentional resources are required for complex tasks, such as perturbations (Shumway-Cook & Woollacott, 2000). The successful accomplishment of these tasks depends on the complexity of each. In the event of varying task complexities, usually, the task with less attention demand will be favored (Chipunza & Mandeya, 2005). As successful trip recovery itself requires a considerable amount of attention, an added secondary and a tertiary task cause a significantly divided attention in the participants. Therefore, it can be considered that a significant amount of cognitive processing is required during TT, which was not available for the participants due to the limited attention capacity of the human brain.

Ankle joint kinematics before and after physical fatigue

The present study demonstrates greater PF activity during post-fatigue trip recovery responses compared to pre-fatigue trip recovery responses. This has been independently observed by previous researchers as well. Granacher et al. (2010) conducted a study to investigate the responses to gait perturbations before and after plantar flexor and dorsiflexor fatigue. They observed a significant decrease in functional reflex activity in the tibialis anterior (TA) muscle after fatigue, which potentially explains the increased post-fatigue PF activity in the present study.

The occurrence of greater PF activity following physical fatigue warrants further investigation. One explanation for that could be the multi-joint fatigue induced in the present study participants was caused by using repeated stand-to-sit exercises as the fatiguing protocol. It has been shown that compared to single-joint fatigue, the individuals perceive multi-joint fatigue as more substantial; thus, they tend to acquire more “braced” postural control responses in order to prevent a fall (Rashedi et al., 2016). Therefore, this increased PF during post-fatigue could be a bracing mechanism acquired by the participants.

From the lowering-hit and elevating-hit strategies, younger individuals commonly acquire the elevating-hit strategy during trip responses (Pijnappels et al., 2004). However, in this study, the participants predominantly acquired the lowering-hit strategy. In the Pijnappels et al. (2004) study, the participants walked on a platform and were tripped using an aluminum trip hazard located at different places on the platform. Since the kinematics and postural control mechanisms are shown to be different according to the tripping method (Troy & Grabiner, 2005), the prominent acquisition of the lowering-hit strategy could have occurred due to the differences in methodology.

There were some limitations of this study. The trips were induced manually; thus, they may not represent the real-world trips. In addition, ankle kinematic measurements alone may not be able to understand the recovery foot positioning adjustments. Moreover, the walking speed would have affected the trip recovery responses. It has been shown that individuals who walk slowly have better responses to postural perturbations (Dingwell & Marin, 2006), probably due to the availability of a greater time to plan and execute a recovery mechanism at slower speeds. Therefore, the joint kinematic variability must be smaller when walking at slower speeds. In the present study, the participants were advised to walk at a self-selected pace to mimic the real-world conditions better. Thus, the variability of walking speeds among participants may have caused differences in joint kinematics. Additionally, since it was not the focus of this study, the accuracy of the secondary cognitive task was not taken into account. However, if the accuracy of the cognitive task was measured, it could have given a better insight into assessing the "posture-first strategy" during CDT. Future studies could be directed towards including different trip induction methods, knee joint kinematics, hip joint kinematics, and kinetics (ground reaction force, moment). In addition, assessing muscle activity using electromyography, analyzing both legs during the trip response, and investigating different populations may yield interesting findings.

Conclusion

Intrinsic factors such as attention, fatigue, and anticipation, as well as extrinsic factors such as task/s at hand, affect the trip recovery. Concurrent cognitive tasks, such as avoiding hazards, and concurrent motor tasks, such as load carriage, are prevalent in ergonomic settings. This study investigated the ankle joint kinematics in unexpected and expected trip responses during dual-tasking, triple-tasking, and fatigue. According to the results, greater DF was observed during UT compared to NG, MDT compared to ST, and TT compared to ST, while greater PF was observed during ET compared to NG and post-fatigue compared to pre-fatigue. These results demonstrate the differences in trip recovery responses in UT, ET, during dual-tasking, triple-tasking, and post-fatigue. The findings of the study would contribute to the limited trip recovery biomechanics literature, especially in young, healthy adults. Moreover, results from this study show that joint kinematics can be assumed during and after a trip, which could be used for better trip prediction, prevention, and recovery. Kinematic adjustments witnessed in the current study could be used to alleviate balance perturbations, which could be used for fall training in the ergonomic population.

References

Aaslund, M. K., Helbostad, J. L., & Moe-Nilssen, R. (2011). Familiarisation to body weight supported treadmill training for patients post-stroke. *Gait & Posture*, *34*(4), 467–472. https://doi.org/https://doi.org/10.1016/j.gaitpost.2011.06.020

Abuin-Porras, V., Villafañe, J. H., Jiménez-Antona, C., Palacios, A., Martínez-Pascual, B., & Rodríguez-Costa, I. (2018). Relationship between attention and balance: a dual-task condition study in children. *Journal of Exercise Rehabilitation*, *14*(3), 349–355. https://doi.org/10.12965/jer.1836142.071

Barbieri, F. A., dos Santos, P. C. R., Simieli, L., Orcioli-Silva, D., van Dieën, J. H., & Gobbi, L. T. B. (2014). Interactions of age and leg muscle fatigue on unobstructed walking and obstacle crossing. *Gait and Posture*, *39*(3), 985–990. https://doi.org/10.1016/j.gaitpost.2013.12.021

Bloem, B. R., Valkenburg, V. V, Slabbekoorn, M., & Willemsen, M. D. (2001). The Multiple Tasks Test: Development and normal strategies. *Gait & Posture*, *14*(3), 191–202. https://doi.org/https://doi.org/10.1016/S0966-6362(01)00141-2

Bureau of Labor Statistics. (2020). A Look at Work Injuries, Illnesses, and Fatalities. https://www.bls.gov/opub/ted/2020/a-look-at-work-injuries-illnesses-and-fatalities-on-workers-memorial-day.htm

Burg, J., Pijnappels, M., & Van Dieen, J. (2005). Out-of-plane trunk movements and trunk muscle activity after a trip during walking. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *165*, 407–412. https://doi.org/10.1007/s00221-005-2312-z

Chipunza, C., & Mandeya, A. (2005). Dual-Task Processing: Effects of Task Difficulty and Stimulus Similarity on Dual-Task Performance. *South African Journal of Psychology*, *35*(4), 684–702. https://doi.org/10.1177/008124630503500405

Dingwell, J. B., & Marin, L. C. (2006). Kinematic variability and local dynamic stability of upper body motions when walking at different speeds. *Journal of Biomechanics*, *39*(3), 444–452. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.12.014

Dong, X. (2005). Long workhours, work scheduling and work-related injuries among construction workers in the United States. *Scandinavian Journal of Work, Environment & Health*, *31*(5), 329–335. http://www.jstor.org/stable/40967512

Elfering, A., Kottwitz, M. U., Häfliger, E., Celik, Z., & Grebner, S. (2018). Interruptions, Unreasonable Tasks, and Quality-Threatening Time Pressure in Home Care: Linked to Attention Deficits and Slips, Trips, and Falls. *Safety and Health at Work*, *9*(4), 434–440. https://doi.org/https://doi.org/10.1016/j.shaw.2018.02.001

Employed persons by detailed industry and age. (2020). https://www.bls.gov/cps/cpsaat18b.htm

Eng, J., Winter, D., & Patla, A. E. (1994). Strategies for Recovery from a Trip in Early and Late Swing during Human Walking. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *102*, 339–349. https://doi.org/10.1007/BF00227520

Ferguson, B. (2014). ACSM's Guidelines for Exercise Testing and Prescription 9th Ed. 2014. *The Journal of the Canadian Chiropractic Association*, *58*(3), 328. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4139760/

Franz, J. R., Francis, C. A., Allen, M. S., & Thelen, D. G. (2017). Visuomotor Entrainment and the Frequency-Dependent Response of Walking Balance to Perturbations. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *25*(8), 1135–1142. https://doi.org/10.1109/TNSRE.2016.2603340

Incidence rates of nonfatal occupational injuries and illness by industry and case types, Bureau of labor statistics, US department of labor. Available from: https://www.bls.gov/. (2017).

Inkol, K. A., Huntley, A. H., & Vallis, L. A. (2018). Do perturbation-evoked responses result in higher reaction time costs depending on the direction and magnitude of perturbation? *Experimental Brain Research*, *236*(6), 1689–1698. https://doi.org/10.1007/s00221-018-5249-8

Kim, S., & Lockhart, T. E. (2008). The effects of 10% front load carriage on the likelihood of slips and falls. *Industrial Health*, *46*(1), 32–39. https://www.ncbi.nlm.nih.gov/pubmed/18270448

Kodithuwakku Arachchige, S.N.K., Chander, H., Turner, A. J., Wilson, S. J., Simpson, J. D., Knight, A. C., Burch V., R. F., Wade, C., Garner, J. C., & Carruth, D. (2020). Muscle Activity during Postural Stability Tasks: Role of Military Footwear and Load Carriage. *Safety*, *6*(35). https://www.mdpi.com/2313-576X/6/3/35#cite

Kodithuwakku Arachchige, Sachini N K, Chander, H., Turner, A. J., & Knight, A. C. (2021). Impact of Prolonged Exposure to a Slippery Surface on Postural Stability. In *International Journal of Environmental Research and Public Health* (Vol. 18, Issue 5). https://doi.org/10.3390/ijerph18052214

Lee, B. C., Kim, C. S., & Seo, K. H. (2019). The Body's Compensatory Responses to Unpredictable Trip and Slip Perturbations Induced by a Programmable Split-Belt Treadmill. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *27*(7), 1389–1396. https://doi.org/10.1109/TNSRE.2019.2921710

Lin, L., Cockerham, D., Chang, Z., & Natividad, G. (2016). Task Speed and Accuracy Decrease When Multitasking. *Technology, Knowledge and Learning*, *21*. https://doi.org/10.1007/s10758-015-9266-4

Lin, W.-H., Liu, Y.-F., Hsieh, C. C.-C., & Lee, A. J. Y. (2009). Ankle eversion to inversion strength ratio and static balance control in the dominant and non-dominant limbs of young adults. *Journal of Science and Medicine in Sport*, *12*(1), 42–49. https://doi.org/https://doi.org/10.1016/j.jsams.2007.10.001

Maki, B., & McIlroy, W. (2007). Cognitive demands and cortical control of human balance-recovery reactions. *Journal of Neural Transmission (Vienna, Austria : 1996)*, *114*, 1279–1296. https://doi.org/10.1007/s00702-007-0764-y

National Census of Fatal Occupational Injuries. (2020). https://www.bls.gov/news.release/pdf/cfoi.pdf

Norrie, R. G., Maki, B. E., Staines, R. W., & McIlroy, W. E. (2002). The time course of attention shifts following perturbation of upright stance. *Experimental Brain Research*, *146*(3), 315–321. https://doi.org/10.1007/s00221-002-1172-z

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

Paran, I., Nachmani, H., & Melzer, I. (2020). A concurrent attention-demanding task did not interfere with balance recovery function in standing and walking among young adults – An explorative laboratory study. *Human Movement Science*, *73*(September), 102675. https://doi.org/10.1016/j.humov.2020.102675

Park, K., Rosengren, K. S., Horn, G. P., Smith, D. L., & Hsiao-Wecksler, E. T. (2011). Assessing gait changes in firefighters due to fatigue and protective clothing. *Safety Science*, *49*(5), 719–726. https://doi.org/10.1016/j.ssci.2011.01.012

Pater, M. L., Rosenblatt, N. J., & Grabiner, M. D. (2015). Expectation of an upcoming large postural perturbation influences the recovery stepping response and outcome. *Gait & Posture*, *41*(1), 335–337. https://doi.org/10.1016/j.gaitpost.2014.10.026

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2001). Changes in walking pattern caused by the possibility of a tripping reaction. *Gait & Posture*, *14*(1), 11–18. https://doi.org/https://doi.org/10.1016/S0966-6362(01)00110-2

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2004). Contribution of the support limb in control of angular momentum after tripping. *Journal of Biomechanics*, *37*(12), 1811–1818. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.02.038

Pijnappels, M., Bobbert, M. F., & van Dieën, J. H. (2005). How early reactions in the support limb contribute to balance recovery after tripping. *Journal of Biomechanics*, *38*(3), 627–634. https://doi.org/https://doi.org/10.1016/j.jbiomech.2004.03.029

Pijnappels, M., Bobbert, M., & Van Dieen, J. (2005). Control of Support Limb Muscles in Recovery after Tripping in Young and Older Subjects. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *160*, 326–333. https://doi.org/10.1007/s00221-004-2014-y

Qu, X., Xie, Y., Hu, X., & Zhang, H. (2020). Effects of Fatigue on Balance Recovery From Unexpected Trips. *Human Factors*, *62*(6), 919–927. https://doi.org/10.1177/0018720819858794

Rashedi, E., Songra, R., Lockhart, T., & Nussbaum, M. (2016, August). Effects of Plantarflexor Muscle Fatigue on Gait Characteristics. *40th Annual Meeting of the American Society of Biomechanics*.

Ratel, S., Duché, P., & Williams, C. A. (2006). Muscle Fatigue during High-Intensity Exercise in Children. *Sports Medicine*, *36*(12), 1031–1065. https://doi.org/10.2165/00007256-200636120-00004

Shumway-Cook, A., & Woollacott, M. (2000). Attentional demands and postural control: the effect of sensorycontext. *The Journals of Gerontology: Series A*, *55*(1), M10–M16. https://doi.org/10.1093/gerona/55.1.M10

Silver, T. A., Mokha, G. M., & Peacock, C. A. (2016). Exploring fall training adaptations while walking. *Work*, *54*(3), 699–707. https://doi.org/10.3233/WOR-162321

Troy, K., & Grabiner, M. (2005). The presence of an obstacle influences the stepping response during induced trips and surrogate tasks. *Experimental Brain Research. Experimentelle Hirnforschung. Expérimentation Cérébrale*, *161*, 343–350. https://doi.org/10.1007/s00221-004-2078-8

United States Department of Labor, Bureau of Labor Statistics, Census of Fatal Occupational Injuries . (2014).

Wang, T.-Y., Bhatt, T., Yang, F., & Pai, Y.-C. (2012). Adaptive control reduces trip-induced forward gait instability among young adults. *Journal of Biomechanics*, *45*(7), 1169–1175. https://doi.org/https://doi.org/10.1016/j.jbiomech.2012.02.001

Wang, Y., Wang, S., Bolton, R., Kaur, T., & Bhatt, T. (2019). Effects of task - specific obstacle - induced trip - perturbation training : proactive and reactive adaptation to reduce fall - risk in community - dwelling older adults. *Aging Clinical and Experimental Research*, *0123456789*. https://doi.org/10.1007/s40520-019-01268-6

Weerdesteyn, V., Schillings, A. M., Duysens, J., & Van Galen, G. P. (2003). Distraction Affects the Performance of Obstacle Avoidance During Walking. *Journal of Motor Behavior*, *35*(1), 53–63. https://doi.org/10.1080/00222890309602121

Wickens, C. (1981). *Processing Resources in Attention, Dual Task Performance, and Workload Assessment.* Taler & Francis.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders : Official Journal of the Movement Disorder Society*, *23*(3), 329–472. https://doi.org/10.1002/mds.21720

CHAPTER IV

MANUSCRIPT II: EFFECTS OF VIRTUAL HEIGHTS, DUAL TASKING, AND TRAINING ON STATIC POSTURAL STABILITY

Introduction

According to the occupational injury data published by the Bureau of Labor Statistics (BLS), from the 880 fatal occupational injuries that occurred in 2019, 711 deaths were due to a fall to a lower level (falling from a height) (*Bureau of Labor Statistics (BLS)*, 2020). During 2011-2016, most falls from heights occurred from ladders, roofs, vehicles, scaffolds, machinery, trees, and stairs, causing 3,722 deaths in workers. Among those, falls from ladders (836 deaths) and roofs (762 deaths) were the most common sources, while falls from over 30 feet have caused the highest number of deaths (658 deaths) from all heights (*Bureau of Labor Statistics, U.S. Department of Labor*, 2018). Falls from heights were commonly observed among construction workers, roofers, tree trimmers, carpenters, and agricultural workers (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor*. 2017). Multiple factors such as general health, fatigue (due to prolonged working hours, lack of sleep, etc.), task/s at hand, divided attention, lack of experience, and environmental factors (rain, snow) increase the fall incidence at the workplace (Chander et al., 2019; Kodithuwakku Arachchige et al., 2020, 2021). While fatal outcomes, permanent/temporal disability, and absence from work affect the worker and their family, the workplace also suffers due to reduced productivity and increased economic burden. Therefore, introducing fall prevention strategies to workplaces is mandatory.

Among the distinct causative factors of falls, loss of balance is identified as a significant cause in ergonomic settings (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor*, 2017). Working at an altitude is challenging in many ways, including maintaining postural stability at the altitude, fear of heights, and anxiety. Along with these challenges, the simultaneous job-specific tasks such as walking on a sloped surface (roofers), working under unsatisfactory conditions (smoke and heat in firefighters), carrying objects (construction workers), and making numerous cognitive decisions (all job categories) make it more confronting. Attention is a significant intrinsic factor that impacts postural stability (Abuin-Porras et al., 2018). Over the past years, dual-tasking (DT) has been used to assess attention and its effects on postural control. Although postural control was previously viewed as a semi-automatic process, it is currently considered a process requiring a significant allocation of attentional resources (Bloem et al., 2001). Therefore, an added secondary task during postural control (i.e., DT) could cause hindrances to both activities due to divided attention. Thus, while working at a height, the employees must be extra vigilant, especially when it involves dual or multi-tasking. DT affects static postural stability in real and virtual environments (Mitra et al., 2013; Walsh, 2021). In the ergonomic population, simultaneous performance of cognitive tasks is extremely common. Such cognitive tasks could be reading a notice, identifying a hazard sign, performing a mental math task, or more. The workers may have to perform these tasks on the ground level or while working at an altitude. As mentioned, balance maintenance at an altitude is more challenging than on the ground level. Further, balance decrements at an altitude cause catastrophic results due to the possibility of fall.

Similarly, a failure to perform the concurrent cognitive task could result in dangerous outcomes (e.g., failing to identify a hazard sign). Thus, the workers must be trained to perform successful DT to improve their productivity and minimize possible injuries.

One successful occupational fall prevention strategy is balance training (Cha et al., 2016). Earlier, balance training has been done with the use of traditional methods such as core strength training (Yu et al., 2017), hydrotherapy (Geytenbeek, 2002), and treadmill walking (Cha et al., 2016). However, these training methods may be impractical, time-consuming, sophisticated, and less convenient when applied to ergonomic settings (Geytenbeek, 2002). Due to its simulation ability, affordability, and convenience, virtual reality (VR) based training is currently considered a potential training tool for fall prevention (Cleworth et al., 2012; Simeonov et al., 2005). Additionally, in occupations such as roofing, construction, and firefighting, where training in real environments is not convenient or safe, balance training in virtual environments (VEs) is more feasible and practical (Chander et al., 2020; Shendarkar et al., 2008). Exposure to virtual heights is shown to elicit a negative impact on postural stability and exhibits an indirect relationship with increasing height (Simeonov et al., 2005). Such resulted in postural instability is associated with increased postural sway and altered lower extremity muscle activation patterns (Cleworth et al., 2012; Zaback et al., 2019). Moreover, standing on a virtual edge (e.g., the edge of a roof) increases the postural sway, mainly due to the anxiety that develops in the individuals. Balance training with repeated exposure to VEs improves balance (Cyma-Wejchenig et al., 2020). Cleworth et al. (2012) assessed the participants' static balance upon exposure to different real and virtual heights. They observed postural decrements and perceived postural instability with both real and virtual heights. Thus, they have suggested VR as a successful method of mimicking real-world simulations.

However, thus far, the studies conducted on the application of VR-based training have mainly focused on the elderly and pathological populations. The number of studies conducted on young, healthy adults is minimal. Moreover, the few studies conducted on VR-based training in the occupational population were limited to ground-level training (Lavender et al., 2019). Due to this dearth of literature, little is known about the application of VR-based training at an altitude among the ergonomic population. Therefore, the purpose of this study was to investigate the impact of virtual heights, DT, and training on static postural stability in a young, healthy population. It was hypothesized that virtual altitudes and DT cause greater static balance decrements, while static balance performance will improve over the two days of testing and be retained after 48 hours.

Methodology

Participants

Twenty-eight collegiate volunteers (14 females; all right leg dominant; age 20.48 ± 1.26 years; height 172.67 ±6.66 cm; mass 69.52 ± 13.78 kg; body mass index 23.32 ± 3.54 kg/m^2) with no history of musculoskeletal, neurological, visual, and vestibular abnormalities were recruited for the study. Only recreationally active individuals [a minimum of aerobic exercises 3-4 days/ week or 150min/ week and resistance training two days/week for the last three months- ACSM guidelines (Ferguson, 2014)] were included in the study. Individuals with simulator sickness, motion sickness, and acrophobia were excluded.

Study Design

The study was approved by the university Institutional Review Board (IRB # 21-416). The study followed a repeated measures design with a counterbalanced virtual environment (VE) assignment. The testing environments were as follows: [ground level (G), altitude 1 (A1), edge 1 (E1), altitude 2 (A2), edge 2 (E2), altitude 3 (A3), and edge 3 (E3). The altitudes were at the two-story (9.18 m/ 30.11 feet), four-story (17.08 m/ 56.04 feet), and six-story (23.69 m/ 77.72 feet) levels. (Figure 1). The performance at the ground level environment (G) was first collected as a baseline measurement, followed by administering other test conditions in a randomized order.

Figure 9

Virtual environments (VEs) used in the study.

Top left: ground level, top right: altitude 1 (A1); bottom left altitude 2 (A2): bottom right: altitude 3 (A3)

Instrumentation

The environments at different altitudes were captured using a 360 GoPro fusion camera due to its ability to capture high-quality images with an 18 Megapixels resolution (Shojaei et al., 2020). Collected pictures (VEs) were administered through a first-generation Oculus Go headset (Facebook Technologies, Qualcomm, Xiaomi). All pictures were taken at a parking lot that was under construction. The static postural stability was measured using an AMTI force platform (Advanced Mechanical Technology, Inc., MA, USA), and muscle activity was measured using a Noraxon DTS electromyography (EMG) system (Noraxon, Scottsdale, AZ, USA). At certain points of the study (discussed under "experimental procedures," a Simulator Sickness Questionnaire (SSQ) was administered to assess the level of simulator sickness level in the participants (Kennedy et al., 1993). SSQ is a 16-item questionnaire that includes different symptoms (general discomfort, fatigue, vertigo, stomach awareness, headache, nausea, blurred vision, dizziness, and burping). The participants must respond to each symptom by circling one of the four options (None, Slight, Moderate, and Severe), graded on a 4-point scale (0 = none, 1 = slight, 2 = moderate, and 3 = severe). The scores of each item are summed to get the final score (Kennedy et al., 1993). If the SSQ score was equal to or greater than 5 at any point of the study, the data collection was planned to be withheld. A presence questionnaire (PQ) was used at the end of the study to understand the participants' perception of the VEs and how well the VEs represented the real-world scenarios. This questionnaire assesses the participants' subjective experience in 19 questions on a 7-point scale (0 = not at all, 4 = somewhat, 7 = completely) (Witmer & Singer, 1998). The questions in PQ are categorized under four subcategories: involvement, immersion, visual fidelity, and interface quality.

Experimental Procedures

The study was conducted over two consecutive days and a third day after 48 hours from the second day. Once the participants came to the research laboratory on day one, informed consent was obtained, and they were asked to fill out a physical activity readiness questionnaire (PARQ) to identify any existing risk factors. In addition, an initial SSQ was provided to detect any existing simulator sickness. Since this study involves a task of identifying occupational hazards and safety signs, they were familiarized with different occupational hazards they might witness during testing. Then, EMG electrodes were attached to the bilateral tibialis anterior (TA) and medial gastrocnemius (MG) muscles. Afterward, the participants were familiarized with the Oculus headset in a neutral VE (classroom). Immediately after familiarization, the participants filled out a SSQ for the second time.

After the second round of SSQ, the participants were advised to perform maximum voluntary isometric contractions (MVIC) of bilateral TA and MG muscles. Three trials of MVIC for each muscle were recorded. Then, the participants were advised to step on the force plate, and they were exposed to the VEs, starting with the ground level VE and followed by counterbalanced VEs at three altitudes (A1, A2, A3) and three edges (E1, E2, E3). At each VE, the participants completed two trials. During the first trial, the participants looked around only by moving their head and neck while keeping their arms along the body. During the second trial, the participants looked around the same way and identified different occupational hazards seen in the VE. A picture without any hazards was provided for the first trial, and the same VE with occupational hazards was presented for the second trial. During each trial, 20 s of postural sway and muscle activity were recorded using the force plate and EMG, respectively. After every 3rd VE, a 5-minute break was allowed to assess the level of simulator sickness and prevent the occurrence of simulator sickness (Chander et al., 2020). To assess the level of simulator sickness, the participants completed an SSQ. At the end of the testing, the participants completed another round of SSQ and a PQ. The same procedure was repeated on the second and third days at the same altitudes and edges but with different pictures.

Data Acquisition

Force plate data was collected at a 100 Hz rate and analyzed using the bioanalysis software. Average center of pressure displacement along the anterior-posterior direction (COP-X), Average center of pressure displacement along medial-lateral direction (COP-Y), 95% ellipsoid area (95EA), average COP velocity (COP-V), and COP length (COP-L) were used as the postural sway variables of interest. Higher values for the postural sway variables indicate greater postural stability decrements and vice versa. EMG data were collected at a 1500 Hz rate, filtered at 20-250 Hz, and rectified before exporting. Upon exporting data to excel sheets, mean and peak muscle activity for bilateral TA and MG for each trial was determined. In addition, the mean muscle activation percentage for each muscle and each trial were calculated by dividing the mean muscle activity by MVIC for that day and multiplying by 100. MVIC for the corresponding day was obtained by taking the mean of three MVIC trials performed at the beginning of testing.

Data analysis

Each postural sway variable was individually analyzed using a 7 (VE; G, A1, A2, A3, E1, E2, E3) x 3 (DAY; day 1, day 2, day 3) x 2 (TASK; single tasking, dual tasking) repeated measures factorial analysis of variance (ANOVA). Similar 7 x 3 x 2 repeated measures factorial ANOVA analyses were conducted individually for mean muscle activity, peak muscle activity, and mean MVIC% of Right TA (RTA), left TA (LTA), right MG (RMG), and left MG (LMG) muscles. Mauchly's test of sphericity was determined to see if the assumption of sphericity was met. Any main effect significant differences in VE, DAY, and TASK were further analyzed using Bonferroni post hoc comparisons. For all analyses, the alpha level was set at an apriori 0.05, and all analyses were performed using the SPSS 27 statistical software package.

Results

Postural Sway Variables Analyses

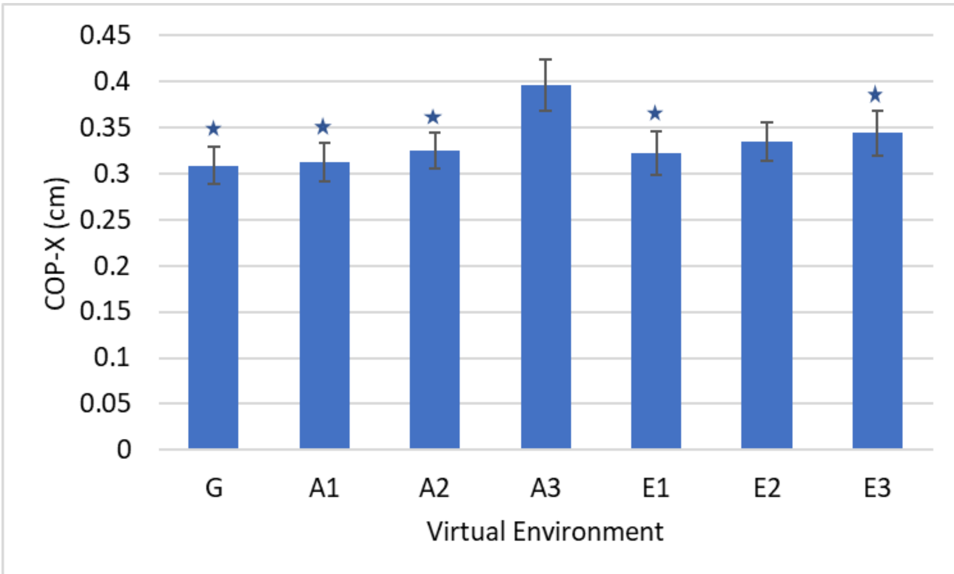
The repeated measures factorial ANOVA revealed significant main effects in all postural sway variables of interest. The assumption of sphericity was violated for VE in all postural sway variable analyses and for DAY in COP-V and COP-V variable analyses. Therefore, a Greenhouse-Geisser correction was used in those violations.

A significant main effect of COP-X was evident in VE (F (6, 162) = 5.94; p < 0.001; ηp^2 = 0.18). Further analysis using Bonferroni post hoc comparisons revealed significant COP-X differences between A3 and G (p = .003), A3 and A1 (p = .001), A3 and A2 (p = .028), E1 (p = .003), and A3 and E3 (p = .012), with higher COP-X in A3 compared to all aforementioned VEs (Figure 2). A significant main effect of COP-X for DAY (F (2, 54) = 4.75; p = .013; ηp^2 = 0.15) revealed significant COP-X differences between DAY 2 and DAY 3 (p = .003), with greater COP-X values during DAY 3 in post hoc analysis (Figure 3). In addition, significant interactions of VE x TASK (F (6, 162) = 4.50; p = .003; ηp^2 = 0.14), DAY x TASK (F (2, 54) = 3.38; p = .041; ηp^2 = 0.11), and VE x DAY x TASK (F (12, 324) = 3.62; p = .002; ηp^2 = 0.12) were revealed for COP-X.

A significant main effect of COP-Y was evident in VEs (F (6, 162) = 2.51; p = .05; ηp^2 = 0.09); however, the post hoc analysis did not demonstrate any significant differences between the VEs. In addition, a significant VE x TASK interaction (F (6, 162) = 3.30; p = .018; ηp^2 = 0.11) was evident in COP-Y analysis.

Figure 10

Average center of pressure displacement along the anterior-posterior direction (COP-X) in different virtual environments.

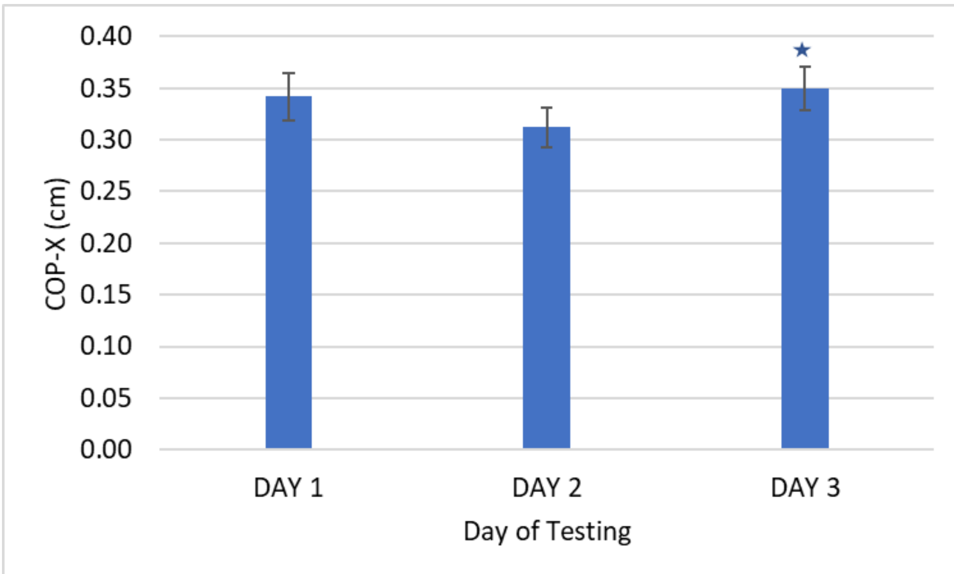


G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from A3.

In the analysis of 95EA, a significant main effect of VEs (*F* (6, 162) = 5.25; $p < 0.001$; $\eta p^2 = 0.16$), were observed. Post hoc comparisons revealed significant differences of 95EA between A3 and G ($p = .011$), A3 and A1 ($p = .007$), A3 and E1 ($p = .013$), and A3 and E3 ($p = .016$) with higher 95EA in A3 compared to all aforementioned VEs (Figure 4). Additionally, a VE x TASK (*F* (6, 162) = 2.66; $p = .042$; $\eta p^2 = 0.09$) interaction was evident in the 95EA analysis.

Figure 11

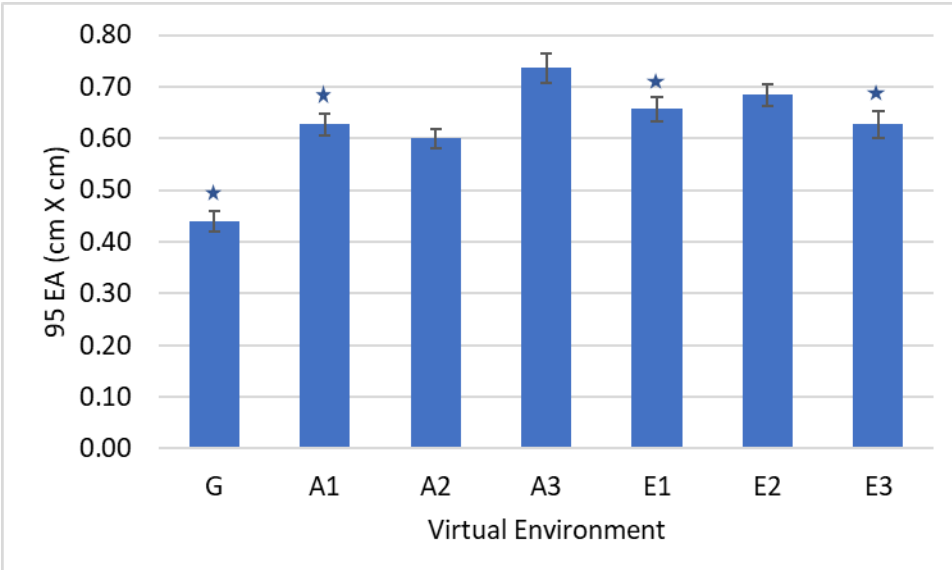
Average center of pressure displacement along the anterior-posterior direction (COP-X) on different days of testing.



Bars represent standard error. ★ denotes significant differences from DAY 2.

Figure 12

95% ellipsoid area (95EA) in different virtual environments.



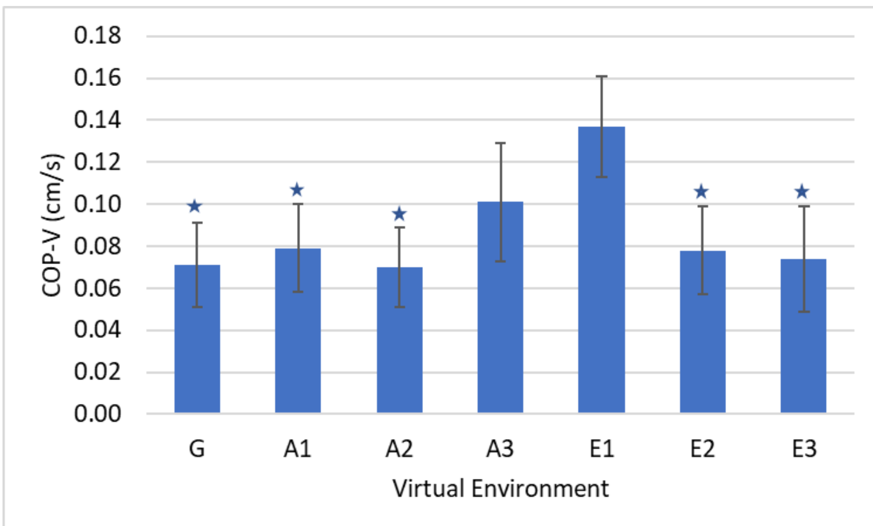
G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from A3.

Furthermore, the analysis showed a significant main effect of COP-V in VE (F (6, 162) = 6.26; p = .005; ηp^2 = 0.19), DAY (F (2, 54) = 10.23; p = .001; ηp^2 = 0.28), and TASK (F (1, 27) = 11.53; p = .002; ηp^2 = 0.30). Post hoc comparisons regarding VEs elicited a similar trend with significant differences of COP-V between A3 and G (p = .029), A3 and A1 (p < .001), A3 and A2 (p = .004), A3 and E2 (p = .001), and A3 and E3 (p < .001) VEs with higher COP-V in A3 compared to all aforementioned VEs (Figure 5). Post hoc comparisons for DAY demonstrated significant differences of COP-V between DAY 1 and DAY 2 (p = .004), as well as between DAY 1 and Day 3 (p = .012) with greater COP-V values for DAY 1, compared to DAY 2 and 3 (Figure 6). Upon observing the descriptive statistics for task, COP-V values were higher for dual tasking (DT), compared to single tasking (ST) (Figure 7). In addition, there were VE x DAY (F

(12, 324) = 5.00; *p* = .02; ηp^2 = 0.16), VE x TASK (*F* (6, 162) = 7.20; *p* = .005; ηp^2 = 0.21), DAY x TASK (*F* (2, 54) = 6.41; *p* = .013; ηp^2 = 0.19), and VE x DAY x TASK (*F* (12, 324) = 7.13; *p* = .007; ηp^2 = 0.21) interactions observed in COP-V.

Figure 13

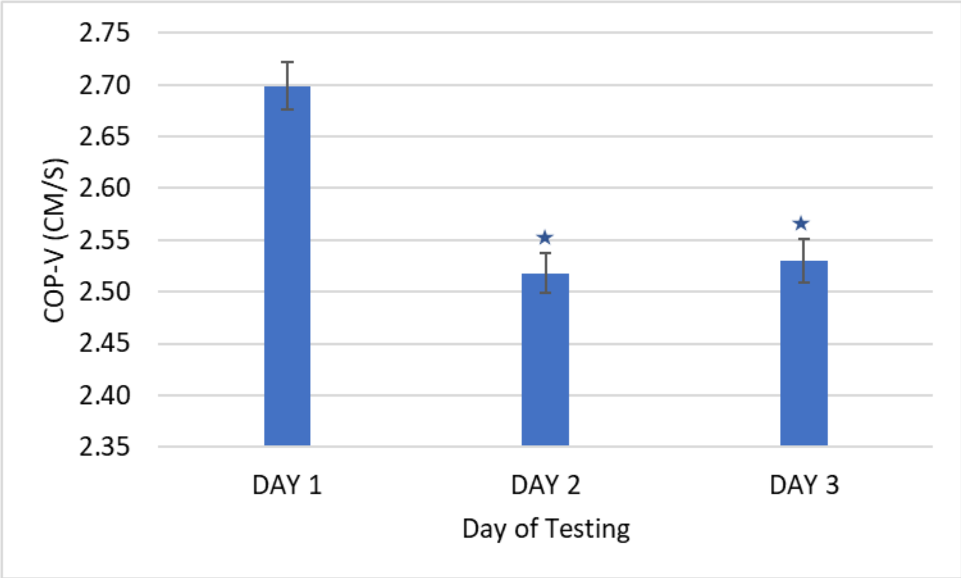
Center of pressure velocity (COP-V) in different virtual environments.



G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from A3.

Figure 14

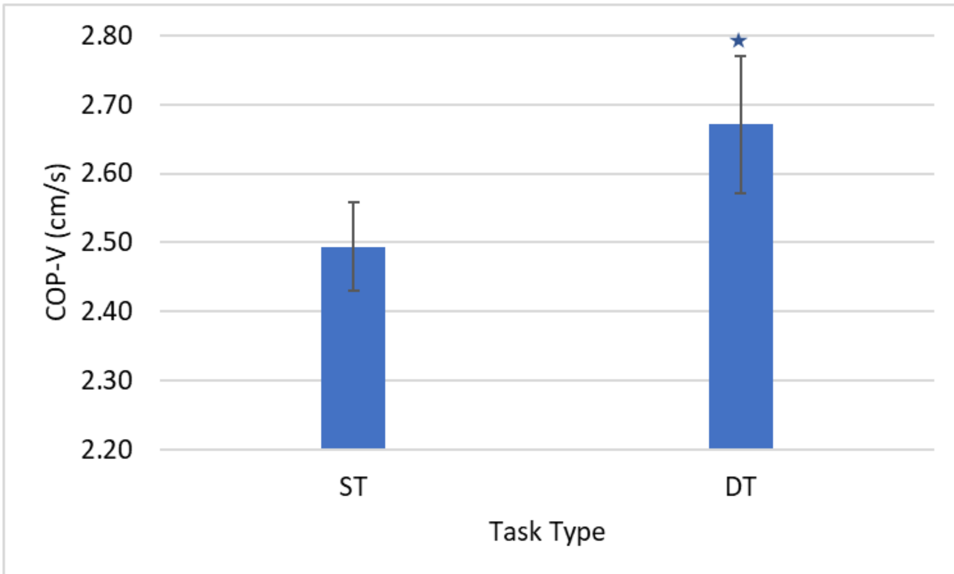
Center of pressure velocity (COP-V) on different days of testing.



Bars represent standard error. ★ denotes significant differences from DAY 1.

Figure 15

Center of pressure velocity (COP-V) during different tasks.



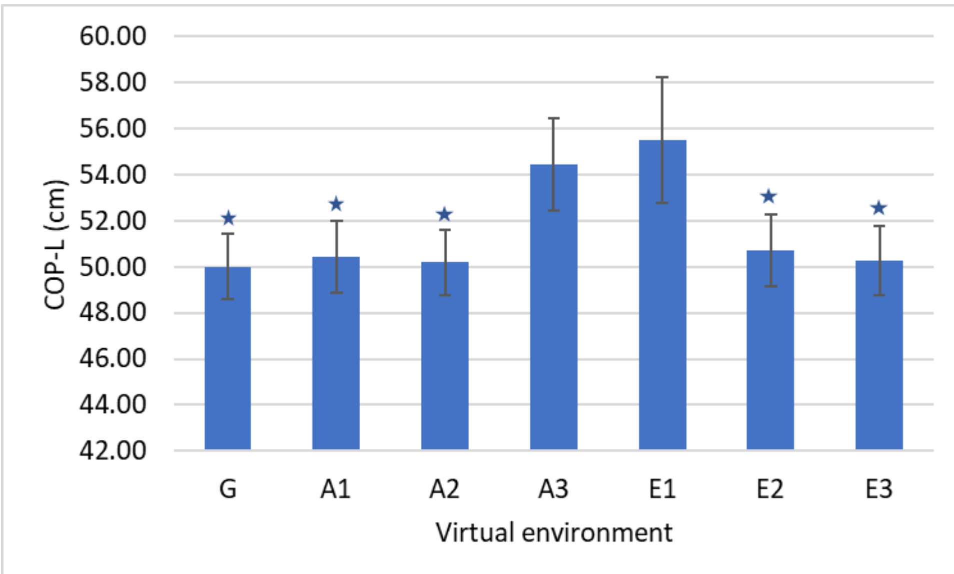
ST: single-tasking; DT: dual tasking. Bars represent standard error. ★ denotes significant differences from ST.

In the analysis of COP-L, significant main effect of COP-L was observed in VE (*F* (6, 162) = 6.26; *p* = .005; $\eta p^2 = 0.19$), DAY (*F* (2, 54) = 10.23; *p* = .001; $\eta p^2 = 0.28$), and TASK (*F* (1, 27) = 11.54; *p* = .002; $\eta p^2 = 0.30$). Post hoc comparisons regarding VEs showed a similar trend with significant differences of COP-L between A3 and G (*p* = .029), A3 and A1 (*p* < .001), A3 and A2 (*p* = .004), E2 (*p* = .001), and A3 and E3 (*p* < .001) VEs with higher COP-L in A3 compared to all the above mentioned VEs (Figure 8). Post hoc comparisons for DAY demonstrated significant differences of COP-L between DAY 1 and DAY 2 (*p* = .004), as well as between DAY 1 and Day 3 (*p* = .012) with greater COP-L values for DAY 1, compared to DAY 2 and 3 (Figure 9). The descriptive statistics for task, showed higher COP-V values were higher for DT, compared to ST (Figure 10). In addition, there were VE x DAY (*F* (12, 324) = 5.00; *p* =

.02; $\eta p^2 = 0.16$), VE x TASK (F (6, 162) = 7.20; p = .005; $\eta p^2 = 0.21$), DAY x TASK (F (2, 54) = 6.41; p = .013; $\eta p^2 = 0.19$), and VE x DAY x TASK (F (12, 324) = 7.13; p = .007; $\eta p^2 = 0.21$) interactions observed in COP-L.

Figure 16

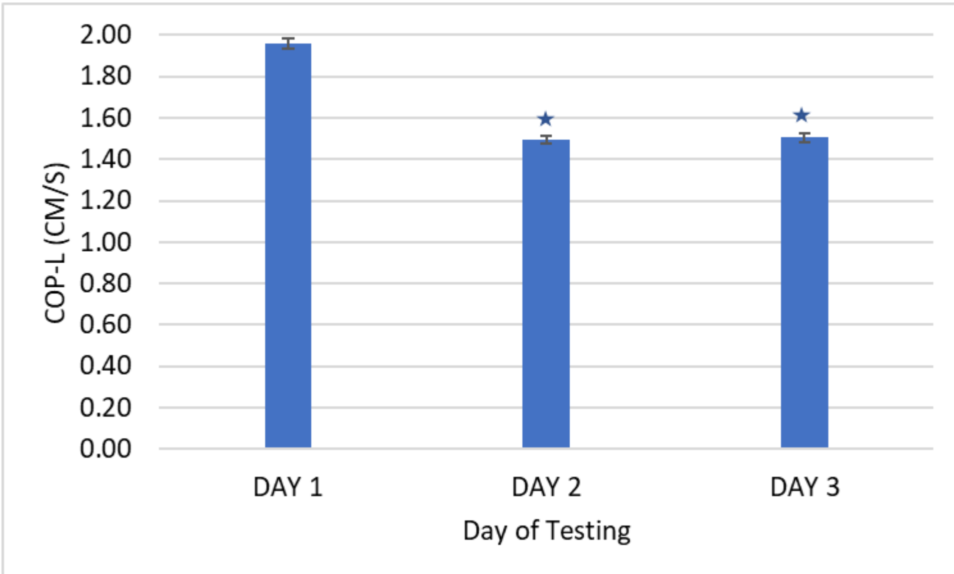
Center of pressure length (COP-L) in different virtual environments.



G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from A3.

Figure 17

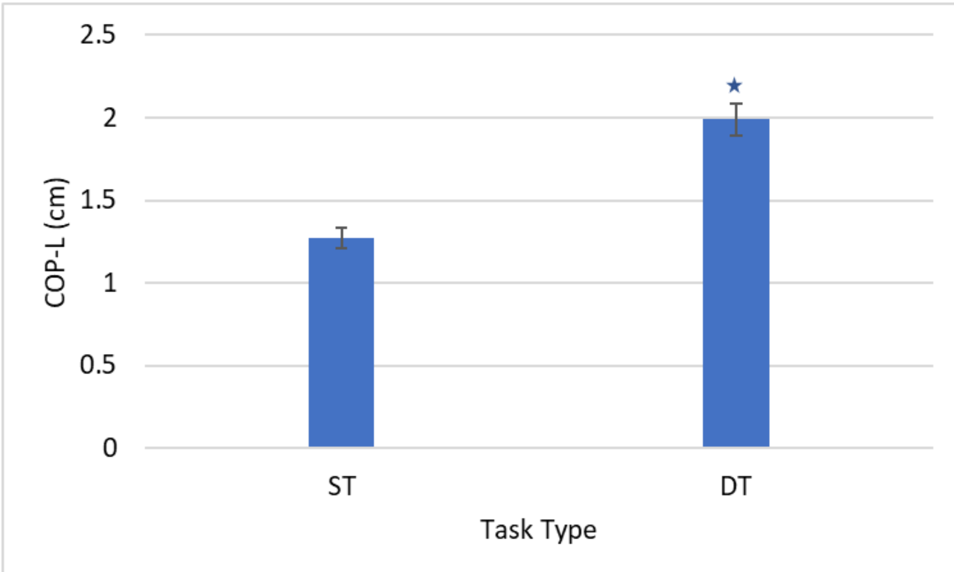
Center of pressure length (COP-L) on different days of testing.



Bars represent standard error. ★ denotes significant differences from DAY 1.

Figure 18

Center of pressure length (COP-L) during different tasks.



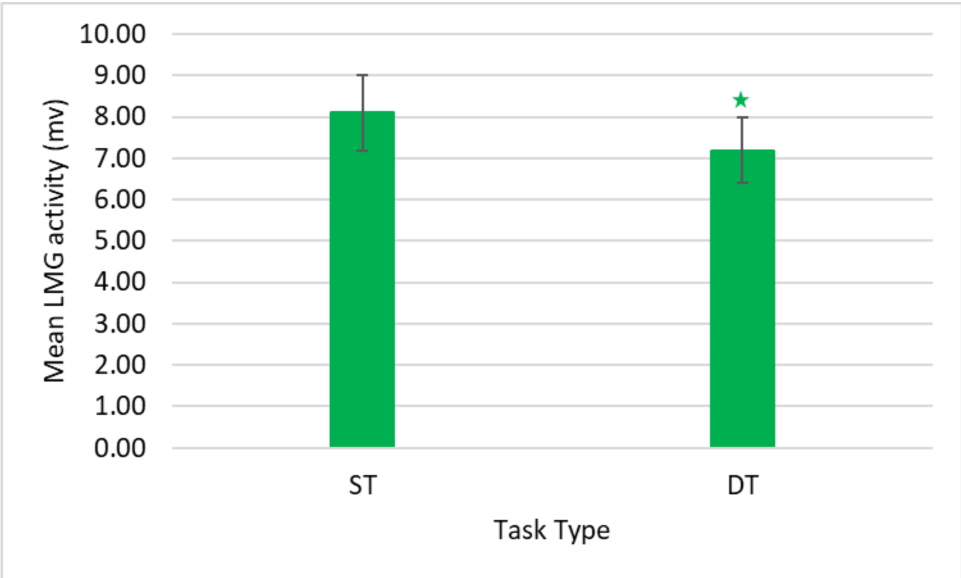
ST: single-tasking; DT: dual tasking. Bars represent standard error. ★ denotes significant differences from ST.

Muscle Activity Analyses

In the analysis of mean muscle activity, a significant main effect of DAY was observed in RTA (F (2, 54) = 4.42; p = .017; ηp^2 = 0.14), with greater mean RTA activity during DAY 1 compared to DAY 3 (p = .041). A significant main effect of VE (F (6, 162) = 2.61; p = .019; ηp^2 = 0.09) and TASK (F (1, 27) = 11.69; p = .002; ηp^2 = 0.30) was observed in RMG, with post hoc analysis revealing greater mean RMG activity during ST compared to DT (p = .002). Post hoc analysis did not show any significant differences of mean RMG activity between VEs. Furthermore, a TASK (F (1, 27) = 16.95; p < 0.001; ηp^2 = 0.39) main effect in LMG was evident with significantly greater mean LMG activity during ST compared to DT (Figure 11). In addition, significant interactions between VE x DAY (F (12, 324) = 2.61; p = .002; ηp^2 = 0.88) and DAY x TASK (F (2, 54) = 4.79; p = .012; ηp^2 = 0.15) was observed in mean RMG activity.

Figure 19

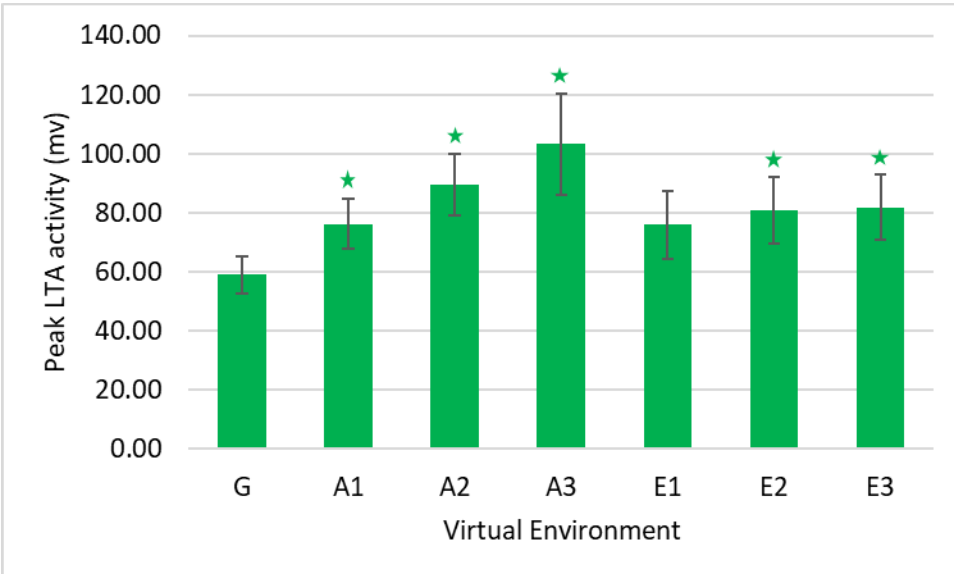
Mean left medial gastrocnemius (LMG) muscle during different tasks.



ST: single-tasking; DT: dual-tasking. Bars represent standard error. ★ denotes significant differences from ST.

Figure 20

Peak left tibialis anterior (LTA) activity in different virtual environments.

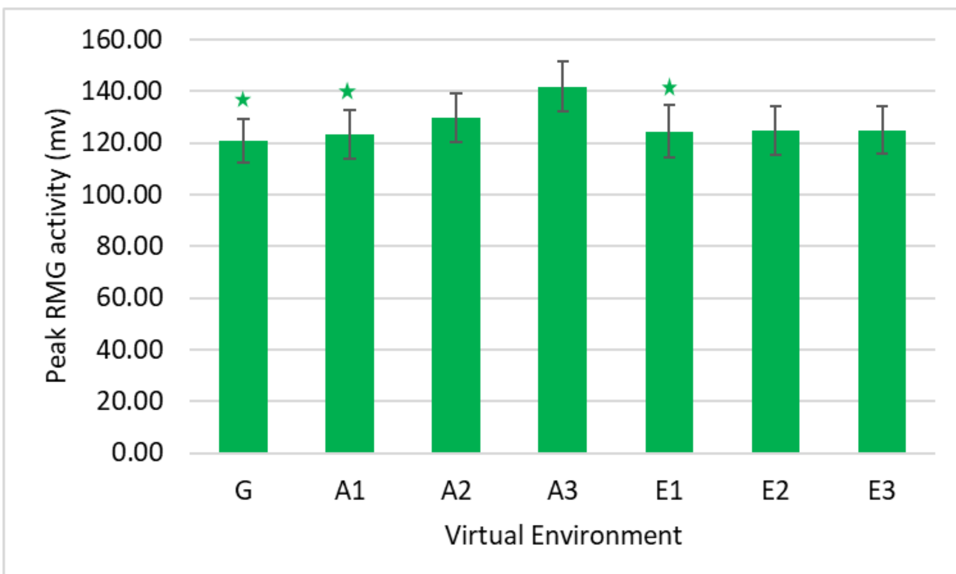


G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from G.

In the peak muscle activity analyses, a significant main effect of VE was reported in RTA (F (6, 162) = 4.83; p = .007; ηp^2 = 0.15), LTA (F (6, 162) = 6.31; p < 0.001; ηp^2 = 0.19), and RMG VE (F (6, 162) = 3.77; p = .008; ηp^2 = 0.12). Since the assumption of sphericity was violated for VE in these analyses, Greenhouse-Geisser correction was used for interpretation. Post hoc analysis for peak RTA was insignificant. However, there were significant differences of peak LTA activity between G and A1 (p = .022), G and A2 (p = .002), G and A3 (p = .026), G and E2 (p = .049), and G and E3 (p = .013) VEs with greater peak LTA activity in all of the above VEs compared to G (Figure 12). Post hoc comparisons for peak RMG activity demonstrated significant differences of peak RMG activity between G and A3 (p = .032), A1 and A3 (p = .005), and E1 and A3 (p = .020) with greater peak RMG activity in A3 compared to all other VEs (Figure 13). Moreover, a significant main effect for DAY (F (2, 54) = 3.69; p = 0.032; ηp^2 = 0.12) in peak RTA activity was revealed with no significant post hoc comparisons. The significant main effect for TASK (F (1, 27) = 5.96; p = 0.021; ηp^2 = 0.18) in peak RMG showed greater peak RMG activity during ST compared to DT. Additionally, a VE x TASK interaction (F (6, 162) = 3.68; p = .015; ηp^2 = 0.12) was evident in the peak LTA activity.

Figure 21

Peak right medial gastrocnemius (RMG) activity in different virtual environments.



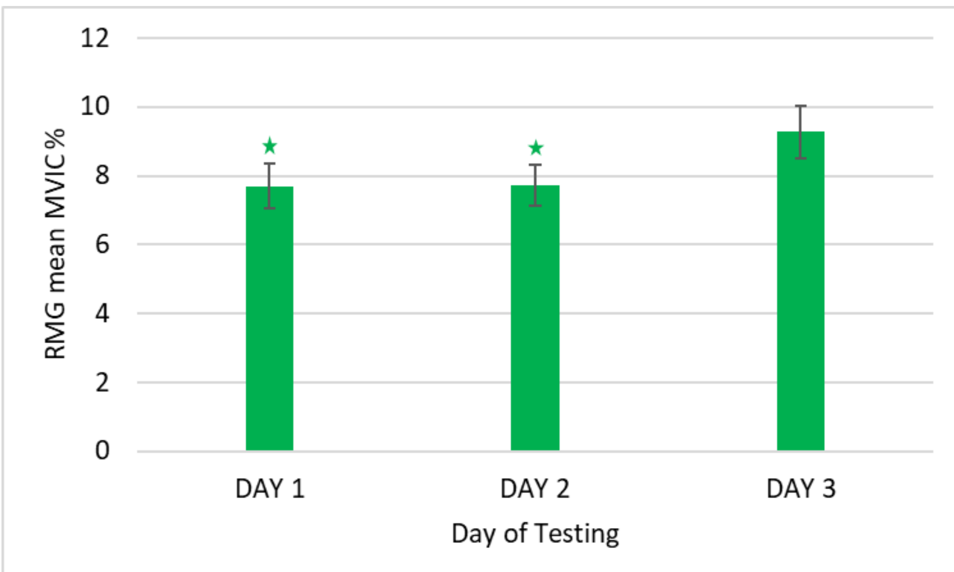
G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from A3.

In the analysis of mean MVIC %, there was a significant main effect of TASK in RMG (F (1, 27) = 11.80; p = 0.002; ηp^2 = 0.30) and LMG (F (1, 27) = 7.8; p = .009; ηp^2 = 0.22), with significantly greater mean MVIC % during ST compared to DT (RMG p = .002; LMG p = .009). The significant main effect of DAY in RMG mean MVIC % (F (2, 54) = 5.02; p = .010; ηp^2 =

0.16) demonstrated greater mean MVIC % during DAY 3 compared to DAY 1 (p = .038) and during DAY 3 compared to DAY 2 (p = .050) (Figure 14). Although a main effect significant difference of RMG mean MVIC % existed in VEs (F (6, 162) = 2.40; p = .030; ηp^2 = 0.08), post hoc analysis was uneventful. In addition to these main effect significant results, an interaction of DAY x TASK (F (2, 54) = 4.20; p = 0.020; ηp^2 = 0.13) was existed in the mean MVIC % of LMG.

Figure 22

Maximum voluntary isometric contraction percentage (MVIC %) of right medial gastrocnemius (RMG) muscle mean activity on different days of testing.



Bars represent standard error. ★ denotes significant differences from DAY 3.

PQ score analysis showed an average value of 61.32 ± 8.92. The descriptive statistics for the subcategories of involvement, immersion, visual fidelity, and interface quality are shown in

Table 1. None of the participants exceeded or matched the value of 5 in SSQ at any point of the study.

Table 2

Mean and Standard Deviation for the subcategories in the Presence Questionnaire.

Subcategory	Mean value	Standard Deviation
Involvement	6.22	0.13
Immersion	5.34	0.17
Visual Fidelity	5.22	0.19
Interface Quality	5.94	0.13

Discussion

The purpose of this study was to investigate the effect of virtual heights, DT, and training on static postural stability. It was hypothesized that virtual altitudes and DT cause greater static balance decrements, while the static balance will improve over the two days of testing and be retained after 48 hours. Overall, the results demonstrated significant differences in static postural stability among the virtual heights (G, A1, A2, A3, E1, E2, E3), task type (ST and DT), and days (day 1, day 2, day 3). More specifically, after analyzing the postural sway variables, greater postural decrements were observed in A3, day 1, and DT conditions than other VEs, days, and ST, respectively. In addition, muscle activity analysis revealed greater muscle activation in A1, A2, A3, E2, and E3 compared to G and in ST compared to DT.

Effect of Virtual Heights on Static Postural Stability

The results revealed significant differences in average center of pressure displacement along the anterior-posterior direction (COP-X), 95% ellipsoid area (95EA), average COP velocity (COP-V), and COP length (COP-L) among the VEs, with higher values for A3, compared to all other VEs. Thus, the participants experienced greater and faster postural sway upon exposure to the A3 virtual environment. A3 is the highest altitude used in this study, resembling the six-story (23.69 m/ 77.72 feet) level (Figure 1), which was taken at the very top of the parking lot that was under construction. Postural instability upon exposure to virtual heights has been shown by multiple researchers independently (Cleworth et al., 2012; Salassa & Zapala, 2009; Simeonov et al., 2005). Simeonov et al. (2005) conducted a study on a young, healthy sample, in which they were exposed to 0 m, 3 m, and 9 m real and matched virtual heights. The researchers assessed the participants' postural sway using a force platform in the anteroposterior and mediolateral directions and observed that the static postural stability deteriorated with increasing height. In a similar study by Cleworth et al. (2012), young, healthy participants' static balance was assessed upon exposure to 0.8 m and 3.2 m real and virtual heights. The group observed increased postural sway at both real and virtual heights. In addition to these main findings in Cleworth et al. (2012) and Simeonov et al. (2005) studies, with the participants eliciting postural stability reactions in VEs similar to real environments, they suggested that VR has a remarkable simulator capability.

Poor postural stability at high virtual altitudes could occur due to multiple reasons. One possible explanation is the developing anxiety upon exposure to heights. With the exposure to heights, a certain amount of anxiety is common, which increases with increasing heights. A few researchers have studied this anxiety-related postural stability and have shown a relationship between increasing height (real and virtual), increasing anxiety, and decreasing postural stability (Cleworth et al., 2012; Diemer et al., 2016; Huppert et al., 2012, 2020). This increasing anxiety with increasing height is seen even in the individuals who did not have self-reported fear of heights (i.e., acrophobia) (Newman et al., 2020). However, the anxiety and postural instability with increasing heights are extensive in individuals with acrophobia (Newman et al., 2020). Another explanation of the postural instabilities at virtual altitudes could be the sensory conflicts that occur in the VE. During the present study, the participants were physically standing on a force plate, but their visual system provided feedback from an altitude. The visual system is one of the three afferent systems in maintaining postural stability, which is the fastest sensory system that allows humans to react to sudden environmental changes (Horak, 1987; Winter, 1995). Poor vision and obstruction of the visual field are shown to affect this system's capabilities, leading to poor balance (Marigold & Patla, 2007). Thus, the conflicting visual feedback in the VEs could have caused the postural instability.

During quiet stance, a person undergoes a certain amount of anteroposterior sway, known as postural sway, which occurs about the ankle joint due to the moments caused by gravity and body weight. The body weight and ground reaction force (GRF) cause the lower extremity agonist and antagonist muscles (TA and MG) to act about the ankle joint as a pulley system to maintain postural stability (Sasagawa et al., 2013; Winter, 2009). Thus, changes in TA and MG activity could be observed depending on the situation and the level of postural perturbations. Upon examining the muscle activity regarding VEs in the present study, significant differences existed in peak LTA activity and peak RMG activity. More specifically, a significantly greater peak LTA activity was observed in A1, A2, A3, E2, and E3 compared to G. This demonstrates that greater muscle activity was utilized to maintain postural stability in A1, A2, A3, E2, and E3 compared to G. In addition, a greater peak RMG activity was observed in A3 compared to G, A1, and E1, indicating that a greater muscle activity used in A3. As postural sway results in VEs do not show significant balance decrements in A1, A2, E1, E2, and E3 compared to G, it can be assumed that the lower extremity muscles were able to preserve the COP excursions with the greater peak muscle activity. However, that greater muscle activation was insufficient to maintain stability in A3, in which balance decrements were observed through postural sway variables. These findings align with previous studies, such as Zaback et al. (2019), in which they assessed the muscle activity of lower extremity muscles upon exposure to real heights. They observed increased muscle activity with altitudes in the TA and soleus muscles. Similar to the present study, Zaback et al. (2019) observed that the participants' postural stability was preserved at the altitudes.

The authors expected to observe significant differences in static postural stability on virtual edges (E1, E2, E3) compared to G, A1, A2, and A3. However, it was not evident in the current study.

Effect of Dual Tasking on Static Postural Stability

In the present study, the participants identified occupational hazards on the VE they were observing, which was considered DT. The results showed significant differences between ST and DT in average COP velocity (COP-V) and COP length (COP-L). More specifically, the magnitude of both COP-V and COP-L were greater during DT compared to ST, demonstrating greater postural sway during DT, indicating balance decrements. Greater static postural instability during DT is commonly shown in the previous literature (Mitra et al., 2013; Walsh, 2021). Mitra et al. (2013) studied the static postural stability of young, healthy individuals with and without cognitive DT. As the cognitive DT, the participants performed a visuo-postural alignment task using a head mount display. They have observed increased anteroposterior and mediolateral postural sway during DT conditions.

The pronounced balance decrements during DT could be attributed to the limited attentional capacity of the human brain. In contrast to single-tasking, DT requires attention to switch between the two tasks; thus, the speed and accuracy of the performance are usually affected in DT (Lin et al., 2016). In the current study, the participants had to maintain their static postural stability while performing a cognitive DT. Both these tasks require a significant allocation of their cognitive resources. In DT, the successful accomplishment of the tasks depends on the complexity of each. In varying task complexities, the task with less attention demand will usually be favored (Chipunza & Mandeya, 2005). As postural control is a highly complex task involving multiple body systems, it was affected in the participants. These findings could be different if the secondary task was a motor task (e.g., carrying a load). In such a situation, both postural control and the secondary motor task are somewhat similar; thus, postural stability might be preserved.

Upon observing the muscle activity results, a significantly greater mean LMG activity and peak RMG were observed during ST compared to DT. Further, significantly increased mean MVIC % in LMG and RMG were observed in ST compared to DT. However, the authors expected to observe greater muscle activity during DT compared to ST. Thus, these findings are opposed to the authors' initial hypothesis. Nonetheless, decreased TA activity during cognitive DT compared to ST is not rare in the previous literature (Vienneau et al., 2022).

Effect of Training on Static Postural Stability

The results of the present study demonstrated significant differences in average center of pressure displacement along the anterior-posterior direction (COP-X), average COP velocity (COP-V), and COP length (COP-L) on day 1, day 2, and day 3. Both COP-V and COP-L showed greater values during day 1 than on day 2 and day 3, indicating improving postural stability on day 2 compared to day 1. In addition, it indicates that the improvements achieved on day 2 have been preserved after 48 hours of training (day 3). This supports that VR can be used as a successful tool for balance training at altitudes. The findings of the study tally with the previous studies that used VR for training purposes (Cleworth et al., 2012; Cyma-Wejchenig et al., 2020; Simeonov et al., 2005). Cyma-Wejchenig et al. (2020) recruited construction workers (age 22-47 years) who usually work at heights. The participants were exposed to twelve 30-minute-long training sessions over six weeks at the ground level and 1 m virtual height during quiet standing. The results revealed that the post-training COP excursions of the training group were significantly lower than the pre-training values. Therefore, the researchers suggested VR-based proprioception training as a great way to improve static postural stability and may potentially replace the traditional balance training methods (Cyma-Wejchenig et al., 2020).

In the present study, the significant difference in COP-X showed higher values for day 3 compared to day 2. This demonstrates that the participants' static postural stability has deteriorated by day 3 compared to day 2. This finding was against the authors' hypothesis, in which better postural stability was expected during day 3, compared to day 2.

Observing the muscle activity differences related to training, RTA mean muscle activity was significantly greater during day 1 compared to day 3. This indicates a lesser requirement of muscle activity to maintain balance on day 3 than on day 1. Therefore, it could be suggested that, during day 3, the maintenance of postural stability was smooth and efficient, reflected by less muscle activity (Lohse et al., 2011), showing positive training effects over time. However, a significantly higher mean MVIC % was observed in RMG on day 3, compared to day 1 and day 2. This was opposed to the authors' hypothesis, in which a lesser mean MVIC % was expected on day 3.

There were certain limitations in the study. The participants were young, healthy, collegiate students with no experience working on a construction site. Thus, the results are only applicable to young, novice construction workers. The pictures were taken at a location where the authors are affiliated to. Thus, during ST, the participants might have tried to recognize the area of the campus rather than passively look around. If they tried to analyze the picture during ST, they have actually performed a DT, even though the trial was supposed to be ST. Future studies could be directed towards experienced workers (construction workers, roofers), assessing co-contraction of the lower extremity agonist/antagonist pairs (especially TA and MG), elderly workers, and workers with a high body mass index.

Conclusion

In occupations such as roofing, construction, and firefighting, falling from heights is extremely common, causing catastrophic outcomes. As training in such real environments is not convenient or safe, balance training in virtual environments (VEs) is more feasible and practical. This study made an effort to assess the effect of virtual altitudes, DT, and training on static postural stability. Overall, the results demonstrate that static postural stability deteriorates at higher virtual altitudes, DT, while it improves with a two-day training. The findings of the study suggest that VR is a great altitude simulator, which could be used as a potential balance training tool in ergonomic settings.

References

Abuin-Porras, V., Villafañe, J. H., Jiménez-Antona, C., Palacios, A., Martínez-Pascual, B., & Rodríguez-Costa, I. (2018). Relationship between attention and balance: a dual-task condition study in children. *Journal of Exercise Rehabilitation*, *14*(3), 349–355. https://doi.org/10.12965/jer.1836142.071

Bloem, B. R., Valkenburg, V. V, Slabbekoorn, M., & Willemsen, M. D. (2001). The Multiple Tasks Test: Development and normal strategies. *Gait & Posture*, *14*(3), 191–202. https://doi.org/https://doi.org/10.1016/S0966-6362(01)00141-2

Bureau of Labor Statistics, U.S. Department of Labor. (2018). Fatal Work-Related Falls to a Lower Level Increased 26 Percent from 2011 to 2016. https://www.bls.gov/opub/ted/2018/fatal-work-related-falls-to-a-lower-level-increased-26-percent-from-2011-to-2016.htm

Bureau of Labor Statistics. (2020). A Look at Work Injuries, Illnesses, and Fatalities. https://www.bls.gov/opub/ted/2020/a-look-at-work-injuries-illnesses-and-fatalities-on-workers-memorial-day.htm

Cha, H.-G., Kim, T.-H., & Kim, M.-K. (2016). Therapeutic efficacy of walking backward and forward on a slope in normal adults. *Journal of Physical Therapy Science*, *28*(6), 1901–1903. https://doi.org/10.1589/jpts.28.1901

Chander, H., Knight, A. C., Garner, J. C., Wade, C., Carruth, D., Wilson, S. J., Gdovin, J. R., & Williams, C. C. (2019). Impact of military type footwear and load carrying workload on postural stability. *Ergonomics*, *62*(1), 103–114. https://doi.org/10.1080/00140139.2018.1521528

Chander, H., Shojaei, A., Deb, S., Kodithuwakku Arachchige, S. N. K., Hudson, C., Knight, A. C., & Carruth, D. W. (2020). Impact of Virtual Reality–Generated Construction Environments at Different Heights on Postural Stability and Fall Risk. *Workplace Health & Safety*, 2165079920934000. https://doi.org/10.1177/2165079920934000

Chipunza, C., & Mandeya, A. (2005). Dual-Task Processing: Effects of Task Difficulty and Stimulus Similarity on Dual-Task Performance. *South African Journal of Psychology*, *35*(4), 684–702. https://doi.org/10.1177/008124630503500405

Cleworth, T. W., Horslen, B. C., & Carpenter, M. G. (2012). Influence of real and virtual heights on standing balance. *Gait & Posture*, *36*(2), 172–176. https://doi.org/https://doi.org/10.1016/j.gaitpost.2012.02.010

Cyma-Wejchenig, M., Tarnas, J., Marciniak, K., & Stemplewski, R. (2020). The influence of proprioceptive training with the use of virtual reality on postural stability of workers working at height. *Sensors (Switzerland)*, *20*(13), 1–17. https://doi.org/10.3390/s20133731

Diemer, J., Lohkamp, N., Mühlberger, A., & Zwanzger, P. (2016). Fear and physiological arousal during a virtual height challenge—effects in patients with acrophobia and healthy controls. *Journal of Anxiety Disorders*, *37*, 30–39. https://doi.org/https://doi.org/10.1016/j.janxdis.2015.10.007

Ferguson, B. (2014). ACSM’s Guidelines for Exercise Testing and Prescription 9th Ed. 2014. *The Journal of the Canadian Chiropractic Association*, *58*(3), 328. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4139760/

Geytenbeek, J. (2002). Evidence for effective hydrotherapy. *Physiotherapy*, *88*(9), 514–529. https://doi.org/10.1016/S0031-9406(05)60134-4

Horak, F. . B. (1987). Clinical measurement of postural control in adults. *Physical Therapy*, *67*(12), 1881–1885. https://doi.org/10.1093/ptj/67.12.1881

Huppert, D., Grill, E., & Brandt, T. (2012). Down on heights? One in three has visual height intolerance. *Journal of Neurology*, *260*. https://doi.org/10.1007/s00415-012-6685-1

Huppert, D., Wuehr, M., & Brandt, T. (2020). Acrophobia and visual height intolerance: advances in epidemiology and mechanisms. *Journal of Neurology*, *267*(1), 231–240. https://doi.org/10.1007/s00415-020-09805-4

Incidence rates of nonfatal occupational injuries and illness by industry and case types, Bureau of labor statistics, US department of labor. Available from: https://www.bls.gov/. (2017).

Kennedy, R., Lane, N., Berbaum, K., & Lilienthal, M. (1993). Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, *3*, 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Kodithuwakku Arachchige, S. N. K., Chander, H., Turner, A. J., & Knight, A. C. (2021). Impact of Prolonged Exposure to a Slippery Surface on Postural Stability. In *International Journal of Environmental Research and Public Health* (Vol. 18, Issue 5). https://doi.org/10.3390/ijerph18052214

Kodithuwakku Arachchige, S. N. K., Chander, H., Turner, A. J., Wilson, S. J., Simpson, J. D., Knight, A. C., Burch V., R. F., Wade, C., Garner, J. C., & Carruth, D. (2020). Muscle activity during postural stability tasks: Role of military footwear and load carriage. *Safety*, *6*(3). https://doi.org/10.3390/safety6030035

Lavender, S. A., Polivka, B. J., Darragh, A. R., Sommerich, C. M., Stredney, D. L., & Wills, C. E. (2019). Evaluating Home Healthcare Workers' Safety Hazard Detection Ability Using Virtual Simulation. *Home Healthcare Now*, *37*(5), 265–272. https://doi.org/10.1097/nhh.0000000000000780

Lin, L., Cockerham, D., Chang, Z., & Natividad, G. (2016). Task Speed and Accuracy Decrease When Multitasking. *Technology, Knowledge and Learning*, *21*. https://doi.org/10.1007/s10758-015-9266-4

Lohse, K., Sherwood, D., & Healy, A. (2011). Neuromuscular Effects of Shifting the Focus of Attention in a Simple Force Production Task. *Journal of Motor Behavior*, *43*, 173–184. https://doi.org/10.1080/00222895.2011.555436

Marigold, D. S., & Patla, A. E. (2007). Gaze fixation patterns for negotiating complex ground terrain. *Neuroscience*, *144*(1), 302–313. https://doi.org/https://doi.org/10.1016/j.neuroscience.2006.09.006

Mitra, S., Knight, A., & Munn, A. (2013). Divergent effects of cognitive load on quiet stance and task-linked postural coordination. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(2), 323–328. https://doi.org/10.1037/a0030588

National Census of Fatal Occupational Injuries. (2020). https://www.bls.gov/news.release/pdf/cfoi.pdf

Newman, V. E., Liddell, B. J., Beesley, T., & Most, S. B. (2020). Failures of executive function when at a height: Negative height-related appraisals are associated with poor executive function during a virtual height stressor. *Acta Psychologica*, *203*, 102984. https://doi.org/https://doi.org/10.1016/j.actpsy.2019.102984

Salassa, J., & Zapala, D. (2009). Love and Fear of Heights: The Pathophysiology and Psychology of Height Imbalance. *Wilderness & Environmental Medicine*, *20*, 378–382. https://doi.org/10.1580/1080-6032-020.004.0378

Sasagawa, S., Shinya, M., & Nakazawa, K. (2013). Interjoint dynamic interaction during constrained human quiet standing examined by induced acceleration analysis. *Journal of Neurophysiology*, *111*(2), 313–322. https://doi.org/10.1152/jn.01082.2012

Shendarkar, A., Vasudevan, K., Lee, S., & Son, Y.-J. (2008). Crowd simulation for emergency response using BDI agents based on immersive virtual reality. *Simulation Modelling Practice and Theory*, *16*(9), 1415–1429. https://doi.org/https://doi.org/10.1016/j.simpat.2008.07.004

Shojaei, A., Rokooei, S., & Mahdavian, A. (2020). *Immersive Video Capture Technology For Construction Management Education VIDEO CAPTURE TECHNOLOGY*. *September*.

Simeonov, P. I., Hsiao, H., DotsonM, B. W., & Ammons, D. E. (2005). Height Effects in Real and Virtual Environments. *Human Factors*, *47*(2), 430–438. https://doi.org/10.1518/0018720054679506

Vienneau, J., Nigg, S., & Nigg, B. M. (2022). Addition of a Cognitive Task During Walking Alters Lower Body Muscle Activity. *Motor Control*, 1–10. https://doi.org/10.1123/mc.2022-0013

Walsh, G. S. (2021). Visuomotor control dynamics of quiet standing under single and dual task conditions in younger and older adults. *Neuroscience Letters*, *761*(February), 136122. https://doi.org/10.1016/j.neulet.2021.136122

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, *3*(4), 193–214. https://doi.org/10.1016/0966-6362(96)82849-9

Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement*. https://books.google.com/books?id=_bFHL08IWfwC

Yu, W., Cha, S., & Seo, S. (2017). The effect of ball exercise on the balance ability of young adults. *Journal of Physical Therapy Science*, *29*(12), 2087–2089. https://doi.org/10.1589/jpts.29.2087

Zaback, M., Adkin, A. L., & Carpenter, M. G. (2019). Adaptation of emotional state and standing balance parameters following repeated exposure to height-induced postural threat. *Scientific Reports*, *9*(1), 1–13. https://doi.org/10.1038/s41598-019-48722-z

CHAPTER V

MANUSCRIPT III: DO VIRTUAL HEIGHTS AND TRAINING AFFECT COGNITIVE PROCESSING IN YOUNG, HEALTHY ADULTS?

Introduction

Occupational categories such as roofers, firefighters, construction workers, and tree trimmers constantly work at heights due to the nature of their occupation. When working at heights, these workers must maintain their postural stability, perform motor tasks related to their occupation, and perform simultaneous cognitive tasks (e.g., identify hazards on-site). Thus, working at an altitude is highly challenging, and those added secondary or tertiary tasks make it more confronting. As a result, falling from heights is extremely common among workers. In 2019, ~81% of 880 fatal occupational injuries occurred due to falling from heights (*Bureau of Labor Statistics (BLS),* 2020). Postural instability is one of the major factors of falls, frequently observed in the ergonomic settings (*Incidence Rates of Nonfatal Occupational Injuries and Illness by Industry and Case Types, BLS, US Department of Labor,* 2017). As a significant contributing factor to the postural instability at altitudes, fear of heights (acrophobia) has been identified (Cleworth et al., 2012; Huppert et al., 2020). Hence, training the working population to counteract this fear in order to prevent falling from heights is mandatory.

According to the American Psychiatric Association, acrophobia is the extreme fear of heights, affecting more than 5% of the general population (American Psychiatric Association, 1994). Similar to panic disorders, individuals with acrophobia experience symptoms related to increased sympathetic activity, such as sweating, tachycardia, hyperventilation, and tremors (Cleworth et al., 2012; Diemer et al., 2016). The individuals who experience acrophobia in real environments usually experience a similar feeling upon exposure to the virtual heights (Diemer et al., 2016). Except for the increased sympathetic activity, exposure to virtual heights triggers other emotions, including anxiety and stress (Cleworth et al., 2012; Fadeev et al., 2020). The human prefrontal cortex regulates a significant proportion of the brain's major executive functions (working memory, task switching, response inhibition). However, the prefrontal cortex is known to be affected by stress hormones (e.g., cortisol) released upon exposure to heights. Thus, exposure to heights has the capability of affecting executive functions (Arnsten, 2009). In addition, fear and anxiety affect motor functions, such as postural control (Cleworth et al., 2012; Newman et al., 2020; Peterson et al., 2018).

Addressing acrophobia includes gradual repeated exposure to heights (American Psychiatric Association, 1994), but exposing an agitated individual to a physical height could endanger their life. Conveniently, virtual reality (VR) has been introduced to assess, train, and address the fear of heights due to its convenience and the absence of physical danger (Wang et al., 2019; Wang et al., 2018). Hence, VR is recognized as a great alternative to exposing individuals to different environments they otherwise avoid due to fear (Cleworth et al., 2012). Due to these favorable features, VR is used as a training tool to overcome the fear of falling from heights, known as VR exposure therapy (VERT) (Fu et al., 2019). Similar to the training to overcome the fear of falling, VR-based training could effectively overcome height-related anxiety (Emmelkamp et al., 2001). In addition to the aforementioned benefits, VR seems to be a promising solution to train workers on dual-tasking (DT) at altitudes as well. However, the appropriate duration of training and retention is yet debatable. When attempting VR-based training in young, healthy adults, it may not require prolonged training as required for the geriatric or clinical populations (Elion et al., 2015).

However, thus far, the studies conducted on VR application to address acrophobia, cognitive processing, and training have mainly focused on the elderly and pathological populations. The number of studies conducted on young, healthy adults and the occupational population is minimal. Moreover, the few studies conducted on VR-based altitude training in the occupational population were limited to ground-level training (Lavender et al., 2019). Due to this dearth of literature, little is known about applying VR-based training at an altitude among the ergonomic population. Therefore, the purpose of this study was to investigate the impact of virtual heights and training on cognitive processing in a young, healthy population. It was hypothesized that the participants' cognitive processing would be better in the virtual ground environment compared to virtual heights and edges. In addition, it was hypothesized that cognitive processing would improve over two training days, and the improvements would be retained after 48 hours of training.

Methodology

Participants

Twenty-eight collegiate volunteers (14 females; all right leg dominant; age 20.48 ± 1.26 years; height 172.67 ±6.66 cm; mass 69.52 ± 13.78 kg; body mass index 23.32 ± 3.54 kg/m^2) with no history of musculoskeletal, neurological, visual, and vestibular abnormalities were recruited for the study. Only recreationally active individuals [a minimum of aerobic exercises 3-4 days/ week or 150min/ week and resistance training two days/week for the last three months-

ACSM guidelines (Ferguson, 2014)] were included in the study. Individuals with simulator sickness, motion sickness, and acrophobia were excluded.

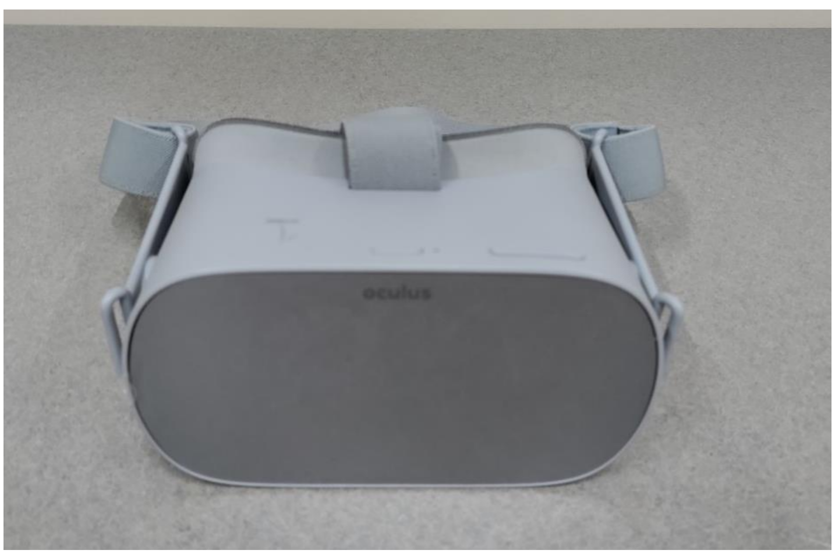
Study Design

The study was approved by the university Institutional Review Board (IRB # 21-416). The study followed a repeated measures design with a counterbalanced virtual environment (VE) assignment. The testing environments were as follows: [ground level (G), altitude 1 (A1), edge 1 (E1), altitude 2 (A2), edge 2 (E2), altitude 3 (A3), and edge 3 (E3). The altitudes were at the two-story (9.18 m/ 30.11 feet), four-story (17.08 m/ 56.04 feet), and six-story (23.69 m/ 77.72 feet) levels. The individuals were first exposed to the ground level environment (G) as a baseline measurement, followed by administering other test conditions in a randomized order.

Instrumentation

Figure 23

Oculus Go headset (Facebook Technologies, Qualcomm, Xiaomi) used in the study.



The environments at different altitudes were captured using a 360 GoPro fusion camera due to its ability to capture high-quality images with an 18 Megapixels resolution (Shojaei et al., 2020). Collected pictures (VEs) were administered through a first-generation Oculus Go headset (Facebook Technologies, Qualcomm, Xiaomi) (Figure 1). All pictures were taken at a parking lot that was under construction. Additionally, as a method to assess the anxiety level, a Polar H10 heart rate (HR) sensor (Polar, USA) was attached to the participant's chest (Diemer et al., 2016). At certain points of the study (discussed under "experimental procedures," a Simulator Sickness Questionnaire (SSQ) was administered to assess the level of simulator sickness level in the participants (Kennedy et al., 1993). SSQ is a 16-item questionnaire that includes different symptoms (general discomfort, fatigue, vertigo, stomach awareness, headache, nausea, blurred vision, dizziness, and burping). The participants must respond to each symptom by circling one of the four options (None, Slight, Moderate, and Severe), graded on a 4-point scale (0 = none, 1 = slight, 2 = moderate, and 3 = severe). The scores of each item are summed to get the final score (Kennedy et al., 1993). If the SSQ score was equal to or greater than 5 at any point of the study, the data collection was planned to be withheld. In addition, at specific points of the study, an Attitudes Towards Heights Questionnaire (ATHQ) and a modified State-Trait Anxiety Inventory Questionnaire (mSTAIQ) were used. ATHQ is a short, 6-item questionnaire regarding how the subjects feel about each height. In ATHQ, the feelings are listed as dichotomous pairs (good/ bad, brilliant/ terrible, pleasant/ unpleasant, safe/ dangerous, non-threatening/ threatening, and not-prejudicial/ prejudicial). Each first adjective is given 0 points, and the second adjective is given 10 points (Abelson & Curtis, 1989). mSTAIQ is also a short, 6-item questionnaire that aids in determining the individuals' anxiety level. It includes responses such as "I feel calm, I'm tense, I feel upset, I'm relaxed, I'm content, and I'm worried" that needed to be answered on a scale of 0 = not at all, 1 = somewhat, 2 = moderately, and 3 = very much (Gjoreski, 2016). Additionally, a presence questionnaire (PQ) was used at the end of the study to understand the participants' perception of the VEs and how well the VEs represented the real-world scenarios. This questionnaire assesses the participants' subjective experience in 19 questions on a 7-point scale (0 = not at all, 4 = somewhat, 7 = completely) (Witmer & Singer, 1998).

Experimental Procedures

The study was conducted over two consecutive days and a third day 48 hours after the second day. Once the participants came to the research laboratory on day one, informed consent was obtained, and an initial SSQ was provided to detect any existing simulator sickness. Since this study involves a task of identifying occupational hazards and safety signs, the participants were familiarized with different occupational hazards they might witness during testing. Afterward, the participants were familiarized with the Oculus headset in a neutral virtual environment (VE). Immediately after familiarization, the participants filled out an SSQ for the second time.

After the second round of SSQ, the participants wore the HR monitor. Upon wearing it, they were advised to sit quietly for 5 minutes to record their resting HR (RHR). Then, the participants were exposed to the VEs, starting with the ground level VE and followed by counterbalanced VEs at three altitudes (A1, A2, A3) and three edges (E1, E2, E3). At each VE, the participants completed two trials. During the first trial, the participants looked around only by moving their head and neck while keeping their arms along the body. During the second trial, the participants looked around the same way and identified different occupational hazards seen in the VE. A picture without any hazards was provided for the first trial, and the same VE with occupational hazards was presented for the second trial. At each VE, there were eight different occupational hazards for the participants to identify. The participants' HR and the number of occupational hazards were identified during each trial. While performing these trials, the participants were standing up on a platform (single-tasking; ST). Hazard identification was added as a secondary task. Hence, the hazard identification was considered a cognitive DT. After every 3rd VE, a 5-minute break was allowed to assess the level of simulator sickness and prevent the occurrence of simulator sickness (Chander et al., 2020). To assess the level of simulator sickness, the participants completed an SSQ. In addition, after completing each VE, the participants completed an ATHQ and a modified STAIQ to assess anxiety and acrophobia levels at each VE. Upon completing the final VE, the participants completed a final SSQ, ATHQ, modified STAIQ, and PQ. The same procedure was repeated on the second and third days at the same altitudes but with different pictures.

Figure 24

A participant wearing the Oculus headset

Data Analysis

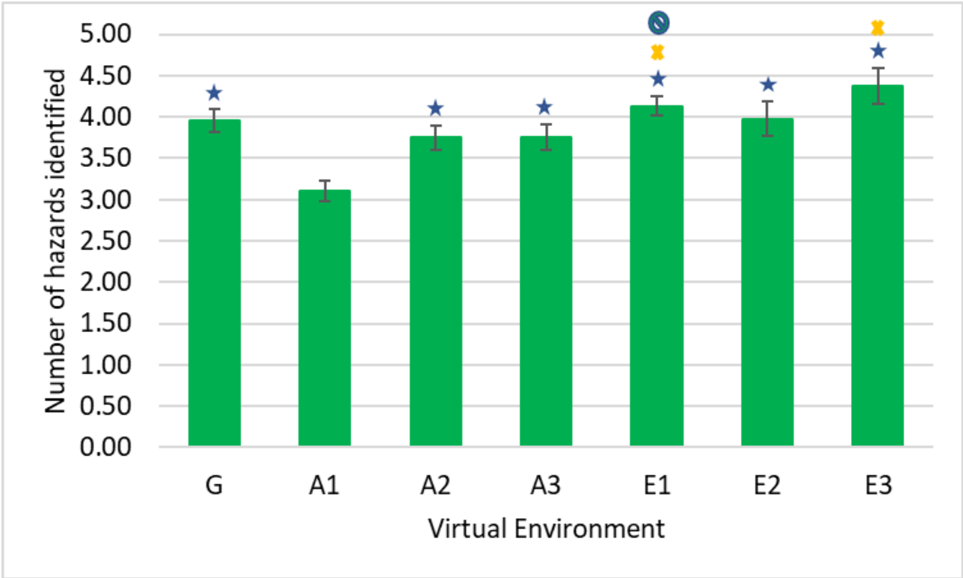
Participants' HR for each VE was divided by the corresponding day's RHR to calculate the percentage increase of RHR for each trial. ATHQ, mSTAIQ, SSQ, and PQ scores were totaled, as explained earlier. The number of hazards identified in each VE and DAY was analyzed using a 7 (VE; G, A1, A2, A3, E1, E2, E3) x 3 (DAY; day 1, day 2, day 3) repeated measures analysis of variance (ANOVA). Similarly, the scores for ATHQ and mSTAIQ were separately analyzed in 7 (VE; G, A1, A2, A3, E1, E2, E3) x 3 (DAY; day 1, day 2, day 3) repeated measures ANOVA. Participants' percentage increase of RHR was analyzed using a 7 (VE; G, A1, A2, A3, E1, E2, E3) x 3 (DAY; day 1, day 2, day 3) x 2 (TASK; single-tasking, dual-tasking) repeated measures factorial ANOVA. Mauchly's test of sphericity was determined to see if the assumption of sphericity was met. Any main effect significant differences in VE, DAY, and TASK were further analyzed using Bonferroni post hoc comparisons. For all analyses, the alpha level was set at an apriori 0.05, and all analyses were performed using the SPSS 27 statistical software package.

Results

The repeated measures ANOVA of the number of hazards identified in each VE and day revealed a significant main effect of the hazards being identified in VEs (F (6, 162) = 12.82; $p <$ 0.001; $\eta p^2 = 0.32$) and DAY (F (2, 54) = 5.94; $p = .049$; $\eta p^2 = 0.11$). Post hoc analysis showed significant differences of the hazard identification between A1 and G ($p < 0.001$), A1 and A2 (p < 0.001), A1 and A3 ($p = .007$), A1 and E1 ($p < 0.001$), A1 and E2 ($p < 0.001$), and A1 and E3 ($p < 0.001$), with lower number of hazards identified on A1, compared to all other VEs. In addition, post hoc comparisons revealed significant differences between A2 and E1 ($p = .040$), A3 and E1 ($p = .019$), and A3 and E3 ($p = .048$), with a lower number of hazards identified on A2 and A3, compared to E1 and E3 (Figure 3). The post hoc comparisons for DAY were uneventful. Additionally, a significant VE x DAY interaction (F (12, 324) = 81.85; $p < 0.001$; $\eta p^2 = 0.75$) was evident.

Figure 25

The number of hazards identified in different virtual environments.



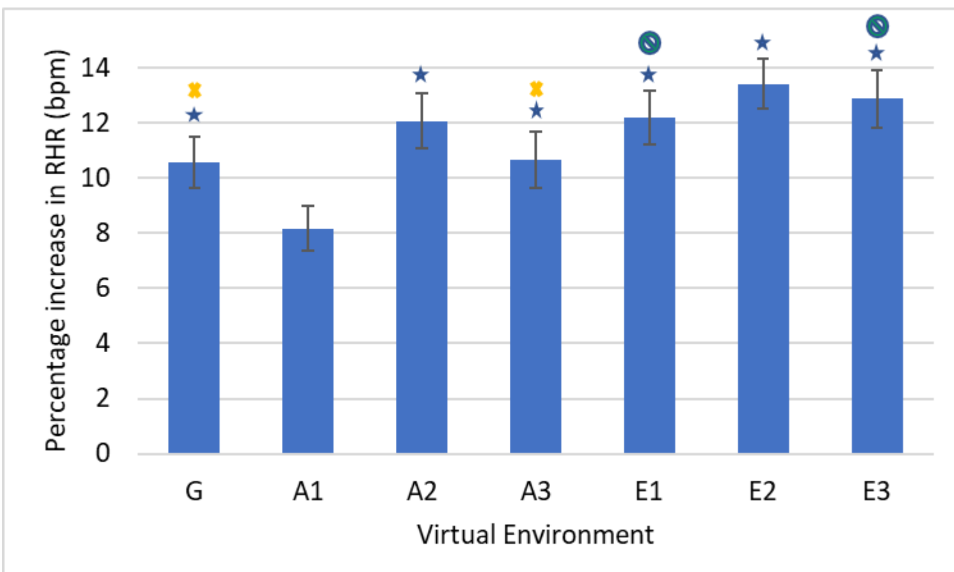
G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from A1, ✖ denotes significant differences from A3, and ⊘ denotes significant differences from A2.

The factorial ANOVA revealed significant differences of percentage increase in RHR in VEs (F (6, 162) = 19.07; p < 0.001; $\eta p^2 = 0.41$), DAY (F (2, 54) = 9.79; p < 0.001; $\eta p^2 = 0.27$), and TASK (F (1, 27) = 32.09; p < 0.001; $\eta p^2 = 0.54$). Post hoc analysis of VEs showed significant differences of the percentage increase in RHR between A1 and G (p = .049), A1 and A2 (p < 0.001), A1 and A3 (p = .003), A1 and E1 (p < 0.001), A1 and E2 (p < 0.001), and A1 and E3 (p < 0.001), with a lower percentage increase in RHR identified on A1, compared to all other VEs. In addition, post hoc comparisons revealed significant differences between G and E2 (p = .002), A3 and E1 (p = .006), A3 and E2 (p < 0.001), and A3 and E3 (p < 0.001), with a lower percentage increase in RHR identified on G and A3, compared to A2, E1, E2, and E3

(Figure 4). Post hoc comparisons of DAY revealed significant differences between DAY 3 and Day 1 ($p < 0.001$) as well as DAY 3 and DAY 2 ($p = .002$), with a lower percentage increase in RHR in DAY 3, compared to DAY 1 and DAY 2 (Figure 5). Comparing DT and ST, a lower percentage increase in RHR was observed during ST, compared to DT ($p < 0.002$) (Figure 6). In addition, significant interactions between VE x DAY (F (12, 324) = 3.97; $p = .002$; $\eta p^2 = 0.13$), VE x TASK (F (6, 162) = 5.97; $p < 0.001$; $\eta p^2 = 0.18$), DAY x TASK (F (2, 54) = 6.60; $p = .003$; $\eta p^2 = 0.20$), and VE x DAY x TASK (F (12, 324) = 5.12; $p < 0.001$; $\eta p^2 = 0.16$) were observed.

Figure 26

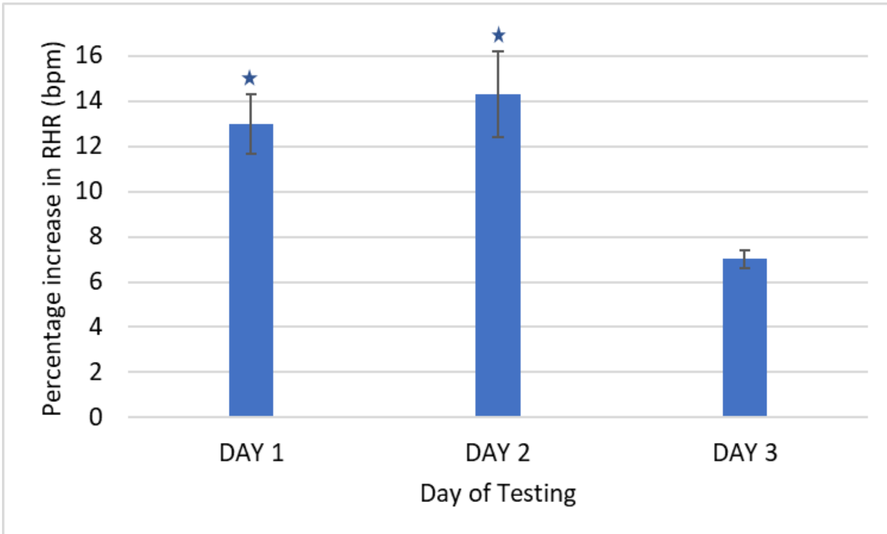
Percentage increase in resting heart rate (RHR) in different virtual environments.



G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from A1, ✖ denotes significant differences from E2, and ⊘ denotes significant differences from E3.

Figure 27

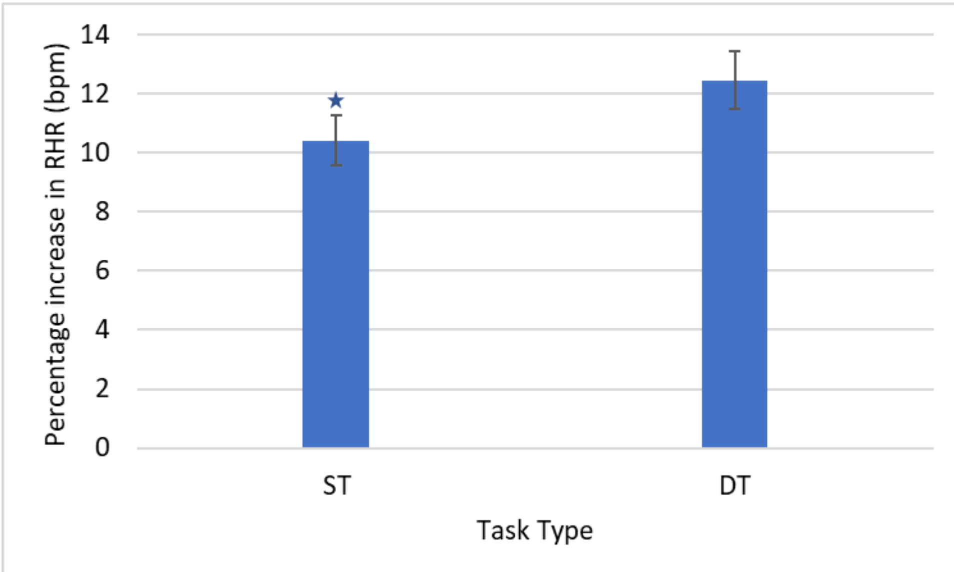
Percentage increase in resting heart rate (RHR) on different days of testing.



★ denotes significant differences from day 3.

Figure 28

Percentage increase in resting heart rate (RHR) during different tasks.

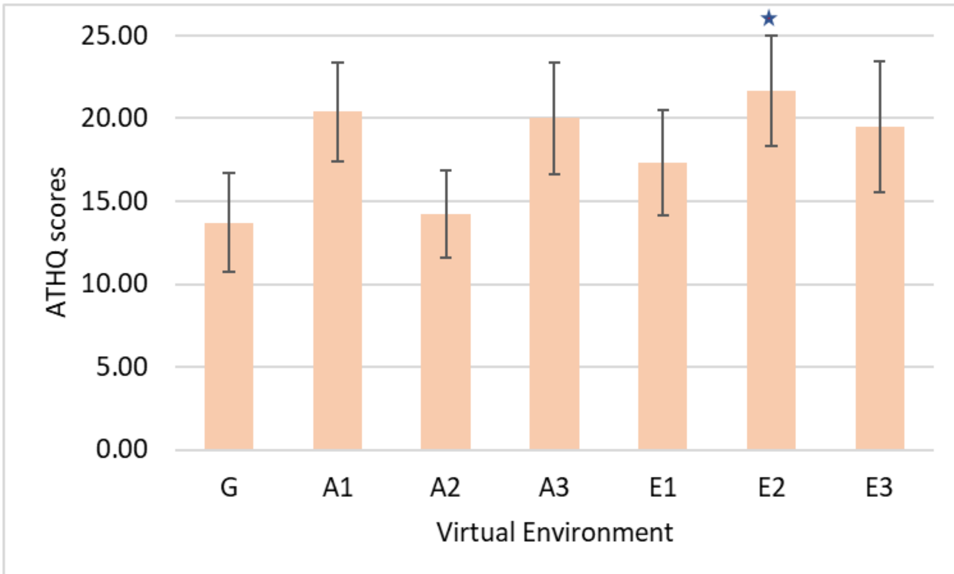


ST: single-tasking; DT: dual-tasking. Bars represent standard error. ★ denotes significant differences from DT.

In the analysis of ATHQ, significant differences were demonstrated among VEs (F (6, 150) = 2.74; p = .039; ηp^2 = 0.20), with significant differences between G and E2 (p = 0.023), with a lower score for G (Figure 7). In addition, a significant interaction between VE x DAY (F (12, 300) = 67.64; p < 0.001; ηp^2 = 0.23). In the analysis of mSTAIQ, there were no significant main effects, except an interaction of VE x DAY (F (12, 324) = 2.67; p = .002; ηp^2 = 0.90). PQ score analysis showed an average value of 61.32 ± 8.92. None of the participants exceeded or matched the value of 5 in SSQ at any point of the study.

Figure 29

Attitude towards heights questionnaire (ATHQ) in different virtual environments.



G: ground level; A1: 2-story level, A2: 4-story level, A3: 6-story level; E1: 2-story level edge, E2: 4-story level edge, A3: 6-story level edge. Bars represent standard error. ★ denotes significant differences from G.

Discussion

The purpose of this study was to investigate the effect of virtual heights and training on cognitive processing in a young, healthy population. It was hypothesized that the participants' cognitive processing would be better in the virtual ground environment compared to virtual heights and edges. It was also hypothesized that cognitive processing would improve over two training days, and the improvements would be retained after 48 hours of training. The height-related anxiety, measured using HR, ATHQ, and mSTAIQ, was hypothesized to decrease over three days.

In the present study, the number of hazards identified was considered a measure of cognitive processing. Overall, the results of the hazard identification revealed a lower number of hazards identified on A1 than all other VEs. In addition, a lower number of hazards were identified on A2 and A3 compared to E1 and E3. Thus, the participants' cognitive processing was most affected in the A1 condition, followed by E1, and then E3. This matches the authors' original hypothesis, in which the cognitive processing was predicted to be best at the ground level compared to virtual edges and heights. These results agree with previous researchers who have shown that virtual heights affect cognitive processing (Cleworth et al., 2012; Fadeev et al., 2020; Kaur et al., 2019; Newman et al., 2020). Newman et al. (2020) exposed young, healthy participants to different virtual heights (ground level, low VR height, and high VR height) while sitting on a chair. They used a GO/NOGO task to measure cognitive processing and have observed that the participants' cognitive processing (working memory and response inhibition) was significantly affected at VR heights compared to the VR ground level. The authors explained that the increased stress-induced cortisol levels could have affected cognitive functions. At an altitude, fear develops due to the conflict between visual inputs with the cognitive processing and the perception of the absent boundaries, triggering an "unsafe" feeling (Huppert et al., 2012). The fear, anxiety, stress, and increasing the sympathetic activity of the body affect the worker's s cognitive performance at altitudes (Cleworth et al., 2012; Fadeev et al., 2020; Kaur et al., 2019).

A greater amount of cognitive processing was expected to be observed during DAY 2 and DAY 3 than on DAY 1. Although a significant main effect of DAY was evident, post hoc comparison did not yield anything significant. However, observing the descriptive statistics, the number of hazards identified on DAY 1 was lower than on DAY 2 and 3. The number of studies that were conducted on training young individuals at an altitude using VR is extremely rare in the previous literature. The studies on VR-based training on cognition have mainly focused on the geriatric or clinical populations (Liao et al., 2014). Therefore, more research are needed to assess the improvement of cognition with VR-based training among young, healthy adults.

The findings regarding the HR were against the authors' hypothesis. The authors expected to observe a greater percentage increase in RHR as the height increases. However, the percentage increase in HR was lowest on A1, followed by G, and then A3. The HR was used as a measure to assess anxiety levels in the present study. According to these results, the participants were least anxious on the A1, G, and A3 levels, which contradicts the hypothesis. This has been observed by previous authors such as Simeonov et al. (2005), who conducted a study on a young, healthy sample in which they were exposed to 0 m, 3 m, and 9 m real and matched virtual heights. The researchers assessed some physiological parameters, including HR as a measurement of anxiety. Although they have observed a direct relationship between HR and the real heights, that was not observed in the VEs (Simeonov et al., 2005). This probably could be due to the knowledge of the absence of physical danger in the VEs, and the use of a young, healthy population without acrophobia. In a clinical or geriatric population, the findings might be different. However, the participants had a lower percentage increase in RHR on DAY 3 compared to DAY 1 and 2. This aligns with the authors' original hypothesis, in which the height-related anxiety was expected to decrease over the three days of testing. In addition, the percentage increase in RHR was lower during ST than DT, potentially demonstrating the participants were less anxious during ST. Moreover, ATHQ yielded significantly lower anxiety values during G compared to E2. Except for that, the anxiety-related questionnaires (ATHQ, mSTAIQ) did not yield any significant findings. Hence, those subjective questionnaires may not be the perfect way to assess anxiety.

There were some limitations in the study. The participants were young and healthy and may have had VR experience. This could have affected the results, especially the findings related to HR. In addition, the participants' attention focus was not controlled in the study. With the participants being young and healthy individuals with no fall history, they might have involved external focus, which could affect the results. Investigating clinical and geriatric populations, individuals with acrophobia, and individuals with zero previous VR exposure could yield interesting findings. In addition, the population being young adults, the results are only applicable to young, novice construction workers. Further research are warranted on the workers with different levels of experience.

Conclusion

Virtual height exposure is associated with reduced cognitive performance while potentially increasing the cognitive load. VR could be a suitable solution to address this affected cognition; however, further studies are needed to understand the effect of VR-based training in young healthy adults. The findings of this study will provide insights into cognitive dual-tasking at altitudes and its challenges, which will eventually aid in minimizing injuries at the workplace.

References

Abelson, J. L., & Curtis, G. C. (1989). Cardiac and neuroendocrine responses to exposure therapy in height phobics: Desynchrony within the 'physiological response system.' *Behaviour Research and Therapy*, *27*(5), 561–567. https://doi.org/https://doi.org/10.1016/0005-7967(89)90091-0

American Psychiatric Association. (1994). *Diagnostic and statistical manual of mental disorders* (A. P. Association (Ed.); 4th ed.).

Arnsten, A. F. T. (2009). Stress signalling pathways that impair prefrontal cortex structure and function. *Nature Reviews. Neuroscience*, *10*(6), 410–422. https://doi.org/10.1038/nrn2648

Bureau of Labor Statistics. (2020). A Look at Work Injuries, Illnesses, and Fatalities. https://www.bls.gov/opub/ted/2020/a-look-at-work-injuries-illnesses-and-fatalities-on-workers-memorial-day.htm

Chander, H., Shojaei, A., Deb, S., Kodithuwakku Arachchige, S. N. K., Hudson, C., Knight, A. C., & Carruth, D. W. (2020). Impact of Virtual Reality–Generated Construction Environments at Different Heights on Postural Stability and Fall Risk. *Workplace Health & Safety*, 2165079920934000. https://doi.org/10.1177/2165079920934000

Cleworth, T. W., Horslen, B. C., & Carpenter, M. G. (2012). Influence of real and virtual heights on standing balance. *Gait & Posture*, *36*(2), 172–176. https://doi.org/https://doi.org/10.1016/j.gaitpost.2012.02.010

Diemer, J., Lohkamp, N., Mühlberger, A., & Zwanzger, P. (2016). Fear and physiological arousal during a virtual height challenge—effects in patients with acrophobia and healthy controls. *Journal of Anxiety Disorders*, *37*, 30–39. https://doi.org/https://doi.org/10.1016/j.janxdis.2015.10.007

Elion, O., Sela, I., Bahat, Y., Siev-Ner, I., Weiss, P. L. (Tamar), & Karni, A. (2015). Balance maintenance as an acquired motor skill: Delayed gains and robust retention after a single session of training in a virtual environment. *Brain Research*, *1609*, 54–62. https://doi.org/https://doi.org/10.1016/j.brainres.2015.03.020

Emmelkamp, P., Bruynzeel, M., Drost, L., & Mast, C. (2001). Virtual Reality Treatment in Acrophobia: A Comparison with Exposure in Vivo. *Cyberpsychology & Behavior : The Impact of the Internet, Multimedia and Virtual Reality on Behavior and Society*, *4*, 335–339. https://doi.org/10.1089/109493101300210222

Eysenck, M., Derakshan, N., Santos, R., & Calvo, M. (2007). Anxiety and Cognitive Performance: Attentional Control Theory. *Emotion (Washington, D.C.)*, *7*, 336–353. https://doi.org/10.1037/1528-3542.7.2.336

Fadeev, K. A., Smirnov, A. S., Zhigalova, O. P., Bazhina, P. S., Tumialis, A. V, & Golokhvast, K. S. (2020). Too Real to Be Virtual: Autonomic and EEG Responses to Extreme Stress Scenarios in Virtual Reality. *Behavioural Neurology*, *2020*, 5758038. https://doi.org/10.1155/2020/5758038

Ferguson, B. (2014). ACSM's Guidelines for Exercise Testing and Prescription 9th Ed. 2014. *The Journal of the Canadian Chiropractic Association*, *58*(3), 328. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4139760/

Fu, Q., Hou, H., Jiang, D., & Liu, Z. (2019). *The Design of Immersion Acrophobia Adjuvant Therapy System (IAATS)* (pp. 447–455). https://doi.org/10.1007/978-981-13-8138-6_38

Gjoreski, M. (2016). *Continuous Stress Monitoring Using a Wrist Device and a Smartphone*. *September 2016*, 86. https://www.researchgate.net/publication/308611962

Huppert, D., Grill, E., & Brandt, T. (2012). Down on heights? One in three has visual height intolerance. *Journal of Neurology*, *260*. https://doi.org/10.1007/s00415-012-6685-1

Huppert, D., Wuehr, M., & Brandt, T. (2020). Acrophobia and visual height intolerance: advances in epidemiology and mechanisms. *Journal of Neurology*, *267*(1), 231–240. https://doi.org/10.1007/s00415-020-09805-4

Incidence rates of nonfatal occupational injuries and illness by industry and case types, Bureau of labor statistics, US department of labor. Available from: https://www.bls.gov/. (2017).

Kaur, R., Sun, R., Ziegelman, L., Sowers, R., & Hernandez, M. (2019). *Using Virtual Reality to Examine the Neural and Physiological Anxiety-Related Responses to Balance-Demanding Target-Reaching Leaning Tasks*. https://doi.org/10.1109/Humanoids43949.2019.9035020

Kennedy, R., Lane, N., Berbaum, K., & Lilienthal, M. (1993). Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, *3*, 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Lavender, S. A., Polivka, B. J., Darragh, A. R., Sommerich, C. M., Stredney, D. L., & Wills, C. E. (2019). Evaluating Home Healthcare Workers' Safety Hazard Detection Ability Using Virtual Simulation. *Home Healthcare Now*, *37*(5), 265–272. https://doi.org/10.1097/nhh.0000000000000780

Liao, Y.-Y., Yang, Y.-R., Cheng, S.-J., Wu, Y.-R., Fuh, J.-L., & Wang, R.-Y. (2014). Virtual Reality–Based Training to Improve Obstacle-Crossing Performance and Dynamic Balance in Patients With Parkinson's Disease. *Neurorehabilitation and Neural Repair*, *29*(7), 658–667. https://doi.org/10.1177/1545968314562111

National Census of Fatal Occupational Injuries. (2020). https://www.bls.gov/news.release/pdf/cfoi.pdf

Newman, V. E., Liddell, B. J., Beesley, T., & Most, S. B. (2020). Failures of executive function when at a height: Negative height-related appraisals are associated with poor executive function during a virtual height stressor. *Acta Psychologica*, *203*, 102984. https://doi.org/https://doi.org/10.1016/j.actpsy.2019.102984

Peterson, S., Furuichi, E., & Ferris, D. (2018). Effects of virtual reality high heights exposure during beam-walking on physiological stress and cognitive loading. *PLOS ONE*, *13*, e0200306. https://doi.org/10.1371/journal.pone.0200306

Shojaei, A., Rokooei, S., & Mahdavian, A. (2020). *Immersive Video Capture Technology For Construction Management Education VIDEO CAPTURE TECHNOLOGY*. *September*.

Simeonov, P. I., Hsiao, H., DotsonM, B. W., & Ammons, D. E. (2005). Height Effects in Real and Virtual Environments. *Human Factors*, *47*(2), 430–438. https://doi.org/10.1518/0018720054679506

Wang, H., Wang, Q., & Hu, F. (2019). Are you afraid of heights and suitable for working at height? *Biomedical Signal Processing and Control*, *52*, 23–31. https://doi.org/https://doi.org/10.1016/j.bspc.2019.03.011

Wang, Q., Wang, H., & Hu, F. (2018). Combining EEG and VR Technology to Assess Fear of Heights. *2018 9th International Conference on Information Technology in Medicine and Education (ITME)*, 110–114. https://doi.org/10.1109/ITME.2018.00034

APPENDIX A

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PARQ)

NAME: ____ DATE: ________________

HEIGHT: _________in.   WEIGHT: __________lbs.   AGE: _________

1) Has your doctor ever said that you have a heart condition and that you should only perform physical activity recommended by a doctor?

2) Do you feel pain in your chest when you perform physical activity?

3) In the past month, have you had chest pain when you were not performing any physical activity?

4) Do you lose your balance because of dizziness or do you ever lose consciousness?

5) Do you have a bone or joint problem that could be made worse by a change in your physical activity?

6) Is your doctor currently prescribing any medication for your blood pressure or for a heart condition?

7) Do you know of any other reason why you should not engage in physical activity?

GENERAL & MEDICAL QUESTIONNAIRE

Occupational Questions

1) What is your current occupation?

2) Does your occupation require extended periods of sitting?

3) Does your occupation require extended periods of repetitive movements? (If yes, please explain.)

4) Does your occupation require you to wear shoes with a heel (dress shoes)?

5) Does your occupation cause you anxiety (mental stress)?

Recreational Questions

6) Do you partake in any recreational activities (golf, tennis, skiing, etc.)? (If yes, please explain.)

7) Do you have any hobbies? (If yes, please explain.)

Medical Questions

8) Have you ever had any pain or injuries (ankle, knee, hip, back, shoulder, etc.)? (If yes, please explain.)

9) Have you ever had any surgeries? (If yes, please explain.)

10) Has a medical doctor ever diagnosed you with a chronic disease, such as coronary heart disease, coronary artery disease, hypertension (high blood pressure), high cholesterol or diabetes? (If yes, please explain.)

11) Are you currently taking any medication? (If yes, please list.)

APPENDIX B

SIMULATOR SICKNESS QUESTIONNAIRE (SSQ)

Please circle the appropriate items below according to your CURRENT feelings with respect to the symptoms listed.

Symptom/feeling	None	Slight	Moderate	Severe
1. General Discomfort	None	Slight	Moderate	Severe
2. Fatigue (Tired)	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eyestrain	None	Slight	Moderate	Severe
5. Difficulty Focusing	None	Slight	Moderate	Severe
6. Salivation Increase (Spit)	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty Concentrating	None	Slight	Moderate	Severe
10. "Fullness of the Head"	None	Slight	Moderate	Severe
11. Blurred Vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. Vertigo (spinning)	None	Slight	Moderate	Severe
15. Stomach Awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

Participants indicating simulator sickness based on SSQ score (a difference > 5 in score from the baseline condition) will be withdrawn from the participation

Source: Kennedy et al., 1993

APPENDIX C

ATTITUDES TOWARDS HEIGHTS QUESTIONNAIRE (ATHQ)

Please indicate how you feel.

1	Good or Bad	
2	Brilliant or Terrible	
3	Pleasant or Unpleasant	
4	Safe or Dangerous	
5	Non-threatening or threatening	
6	Not prejudicial OR prejudicial	

Each first adjective is given 0 points, and the second adjective is given 10 points (Abelson & Curtis, 1989).

APPENDIX D

MODIFIED STATE-TRAIT ANXIETY INVENTORY QUESTIONNAIRE (mSTAIQ)

Please indicate how you feel.

		Not at all	Somewhat	Moderately	Very much
1	I feel calm				
2	I’m tense				
3	I feel upset				
4	I’m relaxed				
5	I’m content				
6	I’m worried				

Points are given as 0 = not at all, 1 = somewhat, 2 = moderately, and 3 = very much (Gjoreski, 2016).

APPENDIX E

PRESENCE QUESTIONNAIRE (PQ)

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer (Witmer & Singer, 1998).

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?
|________|________|________|________|________|________|________|
NOT RESPONSIVE MODERATELY RESPONSIVE COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?
|________|________|________|________|________|________|________|
EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?
|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

5. How natural was the mechanism which controlled movement through the environment?
|________|________|________|________|________|________|________|
EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

6. How compelling was your sense of objects moving through space?

|________|________|________|________|________|________|________|

NOT AT ALL	MODERATELY COMPELLING	VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|________|________|________|________|________|________|________|

NOT CONSISTENT	MODERATELY CONSISTENT	VERY CONSISTENT

8. Were you able to anticipate what would happen next in response to the actions that you performed?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY

9. How completely were you able to actively survey or search the environment using vision?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?

|________|________|________|________|________|________|________|

NOT COMPELLING	MODERATELY COMPELLING	VERY COMPELLING

11. How closely were you able to examine objects?

|________|________|________|________|________|________|________|

NOT AT ALL	PRETTY CLOSELY	VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	EXTENSIVELY

13. How involved were you in the virtual environment experience?

|________|________|________|________|________|________|________|

NOT INVOLVED	MILDLY INVOLVED	COMPLETELY ENGROSSED

14. How much delay did you experience between your actions and expected outcomes?

|________|________|________|________|________|________|________|

NO DELAYS	MODERATE DELAYS	LONG DELAYS

15. How quickly did you adjust to the virtual environment experience?

|________|________|________|________|________|________|________|

NOT AT ALL	SLOWLY	LESS THAN ONE MINUTE

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|________|________|________|________|________|________|________|

NOT PROFICIENT	REASONABLY PROFICIENT	VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|________|________|________|________|________|________|________|

NOT AT ALL	INTERFERED SOMEWHAT	PREVENTED TASK PERFORMANCE

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|________|________|________|________|________|________|________|

NOT AT ALL	INTERFERED SOMEWHAT	INTERFERED GREATLY

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|________|________|________|________|________|________|________|

NOT AT ALL	SOMEWHAT	COMPLETELY