Balance Control when Ascending and Descending Stairs of Different Architectural Designs

by

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Abstract

The purpose of this study was to understand differences in balance control during stair walking on stairs of different architectural designs under varying visual conditions and lighting conditions. An 8-step custom made staircase with removable covers permitted evaluation of stair ambulation. Individuals ascended and descended the staircase under two visual conditions (normal vision, and suboptimal vision), two lighting conditions (bright light and low light) and three architectural stair design conditions (glass treads, open wood risers, and closed wood risers). The main findings of the study showed that older adults positioned their centre of mass further back from the step edge and displayed larger margins of stability across all conditions. In addition, both young and older adults displayed larger margins of stability under the glass stair condition compared to the other stair designs and under the low lighting condition compared to the bright light.
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CHAPTER 1
INTRODUCTION

Stair walking is a necessary skill for independent ambulation and community accessibility. Stair-related accidents are a rapidly growing problem for individuals of all ages, although falling is most prevalent in older adults and those with disabilities, including persons with visual impairments (Startzell et al., 2000). There are many factors that may predispose individuals to sustaining a fall such as stair design, lighting, footwear, distractions, tripping and or overstepping. One of the most common type of irreversible visual impairment in older adults is cataracts. A cataract is a clouding of the lens in the eye that affects vision (CNIB, 2015). Older adults are most likely to develop cataracts (CNIB, 2015), with cataracts representing the second leading cause of blindness in Canada (CNIB, 2015). Currently, more than 2.5 million Canadians are living with cataracts with that number expected to rise to 5 million by 2031 (CNIB, 2015).

It is projected that about one third of people over the age of 65 will fall at least once a year, with this figure escalating to nearly half of those aged 85 and over (Lamoreux et al., 2008). Statistics indicate that fall-related injuries have remained consistently high over the past decades and have a direct burden on the healthcare system with medical costs estimated at $6.6 billion annually (Ontario Injury Compass, 2016). Stairway falls are frequently caused by a combination of different factors including stair design, maintenance, and characteristics of the stair user (Tutton & Campbell, 2013). Each step in a flight of stairs is a physical obstacle that can cause the individual to lose balance and fall due to the potential interference of foot clearance (Johnson & Pauls, 2014). When specifically considering stair design, the risk of falling may be increased due to flaws in construction, non-uniformity of treads, steep step dimensions (Tutton & Campbell, 2013), or perhaps a lack of visibility of the step edge (Hamel et al., 2005). The compromised
ability to negotiate stairs safely can lead to limitations in activities, participation restriction and reduced quality of life (Startzell et al., 2000).

Increased use of various architectural stair designs is becoming more common in our built environment. For example, glass staircases can be a trendy addition to any home or office building, with their popularity rising (Kim & Steinfield, 2014). Unknown, however, is how these types of stairs impact user behaviour and risk of falling. Since the visibility of step edges is an important aspect of stairway safety, it follows that the use of architectural designs such as glass treads may present as a significant risk, due to a potentially diminished step edge contrast. For persons with reductions in contrast sensitivity (such as older adults with cataracts), ability to distinguish the step edge and transitions may be even more compromised (Gittings & Fozard, 1986). Investigation of the age- and vision-related differences in biomechanical measures of user behaviour on stairs of various architectural designs, such as glass treads, can help inform safer design standards. This empirical evidence is important to the adoption of improvements to universal design standards and to inform architectural design education.

The purpose of this study was to understand balance control during stair ambulation on stairs of various architectural designs under modified visual and lighting conditions. Findings from this research will help stakeholders to provide best practice recommendations to reduce falls on stairs.
CHAPTER 2
LITERATURE REVIEW

2.1 Epidemiology of Stair Falls

A fall occurs in response to an unexpected and accidental change in position causing an individual to land at an inferior level such as on an object or the ground, with or without injury (Scott et al., 2010). Falls are the leading cause of injury-related deaths in Ontario (38%). In 2010, more than half (58%) of all hospitalizations due to injuries were related to a fall (Ontario Injury Compass, 2016). One third of community-dwelling Canadian seniors experience a fall each year and half of those will fall multiple times (Scott et al., 2010). Of these falls, approximately 38% of all seniors will be hospitalized for a hip fracture and 39% sustained other types of fractures due to falls (Scott et al., 2010). Half of those who break their hips will not return to full function and independence (Scott et al., 2010). With the number of older persons in Canada anticipated to double by 2036, it is estimated that approximately 3.3 million older adults will fall at least once in 2036 (Scott et al., 2010). Approximately $6.6 billion will be spent on direct health costs for fall related injuries in Ontario (Ontario Injury Compass, 2016).

Not only does falling cause hospitalizations, physical pain, and trauma, leading to disability or premature death, falling also impacts psychological experiences and is known as fear of falling (Arfken et al., 1994). Fear of falling has been considered a health problem among the older population (Cumming et al., 2000). Studies have shown that people who are afraid of falling perform poorly on tests of gait and balance, have poor vision, need assistance with activities of daily living (ADL), and rate their health as poor overall (Cumming et al., 2000). In one study, 21% of women between the ages of 66-70 reported some fear of falling whereas this number increased to 45% for those over the age of 80. Similar values were reported for men (14% and 21% fear of falling rates for younger and older groups of seniors, respectively) (Arfken
et al., 1994). These fear of falling values also represent a direct correlation to quality of life of the individual; 48% of individuals who were fearful of falling stated that they were somewhat or not at all satisfied with life and 25% had scores suggesting depression (Arfken et al., 1994). Fear of falling can have quantifiable psychological consequences that can become more defined with age, with a measurable impact of quality of life and independence.

Stairs have been identified as one of the most common areas of the home leading to falls (Tutton & Campbell, 2013). In Ontario in 2016, injuries related to stairs made up 12% of all emergency department visits for fall-related injuries (Ontario Injury Compass, 2016); these rates have remained relatively constant over the time of 2011 to 2016 (Ontario Injury Compass, 2016). In addition, stair-related falls in Ontario alone accounted for $327 million in total health care costs ($234 million in direct costs and $93 million in indirect costs) (Ontario Injury Compass, 2016). It has been shown that more serious injuries occur when descending a staircase and individuals are three times more likely to sustain a fall during descent compared to ascent, likely in response to the challenge of the task compared to ascent (Reid et al., 2011; Startzell et al., 2000) combined with the increased height at which one can fall if a misstep occurs during descent.

2.2 Phases of Stair Gait

The stair gait cycle is separated into two distinct phases: the stance phase and the swing phase (McFadyen & Winter, 1988). When ascending stairs, the stance phase has three sub-phases, including weight acceptance, pull-up, and forward continuance (McFadyen & Winter, 1988). Weight acceptance is the shifting of the body into an ideal position to step onto the new step. Pull-up is the progression to full support on the next step and forward continuance is when the ascent of a step has been accomplished and progression of movement continues (McFadyen
& Winter, 1988). Similarly, the swing phase is subdivided into two sub-phases. Foot clearance occurs as the raised leg clears the intermediate step. The swing leg is then positioned for foot placement on the next step. Similar to ascent, the stance phase of descent has three sub-phases: weight acceptance, forward continuance and controlled lowering (the body’s mass is lowered onto the support limb) (McFadyen & Winter, 1988) while the swing phase of descent has two-phases that include leg pull through and foot placement (McFadyen & Winter, 1988).

2.3 Balance Control and Stair Ambulation

Ability to control posture is important to carry out many activities of daily living, including stair walking. Both stair ascent and descent can be challenging to one’s balance control, although balance control during stair ascent has been evaluated to a lesser extent than stair descent. (Heasley et al., 2014; McFayden et al., 1988; Reeves et al., 2009; Zachazewski et al., 1993). This is perhaps due to the lesser risk of serious injury if a fall were to occur during ascent compared to descent. Substantially more research focuses on balance control and risk factors of falls during stair descent. Individuals demonstrate reduced frontal plane movement of the upper body during stair ascent when compared to descent (McFadyen & Winter, 1988; Reid et al., 2011). When compared to level ground walking, stair ascent results in a longer mean cycle duration and a shorter proportion of time in stance (Nadeau et al., 2003). In addition, while level walking and stair ascent involve similar hip and knee joint moment patterns, stair ascent comprises primarily of a transfer of muscle energy into potential (gravitational) energy of the body (Nadeau et al., 2003). Therefore, greater hip and knee extension joint moments are required at the beginning of the stance phase compared with level walking. When shifting the body’s COM laterally and upwards for stair ascent or downwards for stair descent, the task of shifting the body's requires the body's mass to be controlled by muscles surrounding the hip, knee and
ankle joints to produce large moments (Watanabe et al., 2016). Compared with level-ground walking, knee joint extension moments are up to two times greater during stair ambulation (Byrne, et al., 2005), thus, one's ability to safely ambulate stairs is reliant in part on sufficient lower limb muscle strength (Watanabe et al., 2016).

Stair descent has been shown to be an inherently more unstable task than stair ascent for healthy young and older adults (Reid et al., 2011), and many persons will choose to use a handrail to enhance perceived or actual stability. To date, several studies have investigated handrail use and balance during stair walking (Reid et al., 2011; Zietz et al., 2011). When completing the task with a handrail, compared to that without a handrail, similar center of pressure velocities have been reported during both ascent and descent (Reid et al., 2011). These results suggest that the handrail does not necessarily increase biomechanical stability (as measured in this study) for healthy individuals (Reid et al., 2011). It should be noted that older adults prefer to use the handrail highlighting the perceived stability afforded by the handrail (Reid et al., 2011). In contrast, Zietz and colleagues (2011) have found that when high risk older adults use the handrail, a reduction in the vertical COM acceleration was shown, suggesting that these individuals loaded the handrail to resist the downward displacement of the COM and improve stability using external support (Zietz et al., 2011).

Although there are certainly risks to balance and falls during ascent, stair descent presents as a larger challenge, with individuals sustaining three times more falls when compared to walking upstairs (Startzell et al., 2000). Stair descent involves the control of the forward acceleration of the large upper body mass with each downward step taken (Novak et al., 2016). When compared to other activities of daily living, stair descent imposes challenges due to constraints of the base of support (BOS). An adult's forefoot placement will generally extend
beyond the edge of the stair tread (Wright et al., 2005), resulting in a restricted anterior BOS limit, which is often defined by the edge of the tread (Novak et al., 2015).

2.3.1 Aging and Balance Control During Stair Walking

The maintenance of motor independence, which includes the ability to ambulate safely up and down stairs, is crucial to health and well-being for older adults (Frank & Patla, 2003). To better understand the effects of aging on balance control during stair ambulation, several studies have reported differences in COM metrics, COM-COP inclination angles, and COM-COP distances (Lee & Chou., 2007; Milan et al., 2007). Both the COM-COP inclination angles and COM-COP distances during walking provides evidence about the capability to control COM position relative to the corresponding COP (Lee & Chou., 2005).

Older men do not significantly alter COM in the plane of progression or medial-lateral plane relative to the COP compared to young adults during both ascent and descent (Mian et al., 2007). Conversely, Lee & Chou (2007) found that older adults demonstrated a significantly greater COM-COP inclination angle during the stair-to-floor transition phase when compared to young adults in the sagittal plane (Lee & Chou., 2007). In the latter case, results suggest that older adults are at a greater risk of falling due to age-related declines in muscle strength which can compromise the ability to quickly minimize the COM sway during the stair-to-floor transition (Lee & Chou., 2007). Older adults have also demonstrated greater lateral upper body tilt angles during steady state stair descent compared to young adults. A greater tilt angle and forward lean is more difficult to recover from due to 60% of the body’s mass being in the upper body, further highlighting an increased falls risk (Novak et al., 2016).

In addition to alterations in the anterior-posterior and frontal plane during stair descent, older adults have demonstrated periods of high COM downward accelerations during both the
landing and lowering phases of descent (Buckley et al., 2013), associated with alterations in muscle activity patterns, further highlighting reduced control of one’s COM with age. During stair descent using a reciprocal stepping pattern, bodyweight becomes supported on a single limb while the forward-reaching limb is lowered to contact the step which in turn is associated with lowering of the COM (Buckley et al., 2013). As noted by the authors, for older adults to generate their movement pattern in a controlled manner, increased ankle and knee joint torque are required relative to that of over ground walking (Buckley et al., 2013). Older adults operate at a higher proportion of their maximum eccentric capacity (Reeves et al., 2008, Novak et al., 2014) and at or beyond the maximum passive reference joint range of motion, which may provide an understanding of the impact of age on COM control.

2.3.2 Margin of Stability

The margin of stability, defined as the distance between the extrapolated center of mass and the anterior base of support, is important to understanding fall risk during gait, particularly in the elderly (Hof et al., 2005). Recently, the margin of stability has been analyzed during stair descent to providing additional insight into balance control during this task (Novak et al., 2016; Bosse et al., 2012).

While descending stairs, it has been reported that older individuals have a reduced capacity to control the body’s COM, a result of a higher COM velocity and a more anterior position of the vertical projection of the COM (Bosse et al., 2012) which leads to a reduced margin of stability with age. Older participants portrayed a smaller and more negative margin of stability (representing an unstable position) at the initiation of the double support phase compared to younger adults due to a higher anterior COM velocity and thus, a more anterior position of the extrapolated COM (Bosse et al., 2012). This may indicate that individuals were in
an energetically efficient state (conserving power) for making the transition to the next state, but a dynamically unstable body position (Bosse et al., 2012). At the beginning of the single support phase (where the trailing leg takes off) older adults also had a more negative margin of stability when compared to the younger adults (Bosse et al., 2012). It is suggested that age-related declines in lower limb strength and muscle power places adults at an increased risk of falls due to the altered ability to safely control the body’s COM while ambulating stairs (Bosse et al., 2012; Reeves et al., 2009). In contrast, Novak et al. (2016) reported larger margins of stability for older adults at foot contact in the anterior-posterior direction compared to younger adults, likely due to slower gait adopted by the older adults in response to the challenge of the task and perhaps a full staircase being used in the study by Novak and colleagues (2016) compared to the 3-step staircase evaluated by Bosse et al., (2012).

2.4 Impact of Suboptimal Visual Information on Balance Control

2.4.1 Epidemiology of Visual Decline

Persons with visual impairment are almost twice as likely to fall and to have recurrent falls and resultant injuries (Lamoreux et al., 2008). Visual acuity is the most common assessment in fall prevention programs (Lamoreux et al., 2008) and risk factor identified in research studies (Ivers et al., 1998; Klein et al., 2003). However, other visual assessments including contrast sensitivity and depth perception have also been shown as important risk factors for falls in older adults (Ivers et al., 1998). In one study, 43.2% of individuals reported falling and 21.7% reported multiple falls on stairs (Ivers et al., 1998); those who reported multiple falls demonstrated reductions in all visual assessments. Impaired depth perception, contrast sensitivity, and low contrast visual acuity were the strongest risk factors determining multiple falls (Klein et al., 2003). This loss of edge-contrast sensitivity may predispose older people to trips over obstacles.
within and outside of the home, such as steps and discontinuities in walkways (Ivers et al., 1998). In addition, majority of people with presbyopia are prescribed multifocal lenses, which provide corrected distance and near vision in the same pair of glasses (Davies et al., 2016). The issue regarding these glasses however, is offset to some degree by optical ‘side-effects’ which can be a huge issue regarding safe stair ambulation (Davies et al., 2016). Little is known about the biomechanics of stair navigation in individuals with multifocal glasses (Davies et al., 2016) however, in one study looking at toe clearance, multifocal glasses increase the variability of toe clearance in older adults navigating stairs and increase fall risk (Renz et al., 2015).

2.4.2 Visual Decline and Balance Control

Visual decline can be thought of as a consequence of normal aging. However, the effects of visual acuity and contrast sensitivity directly impact everyday motor ability and balance control, particularly in maintaining center of mass when ascending and descending stairways. Although no study to date has investigated stair ascent and impact of vision decline on biomechanical outcomes, the effect of age and blurring vision on the dynamics of a stepping-up task of three different heights has been reported (Heasley et al., 2014; Heasley et al., 2005). Taking a single step onto a new level involves moving from a stable, static situation to a dynamic, unstable one, and so a transfer of body weight from one limb to the other occurs (Heasley et al., 2014). In a series of studies, young and older adults performed a step up to a new level of heights 73 and 146 mm (equivalent to a household riser or curb) under two visual conditions - normal or corrected-to-normal vision, and vision blurred by light scattering lenses simulating cataracts. During this task, COM and COP dynamics (in the medial-lateral and anterior-posterior directions), and foot clearance parameters were determined to assess the risk of falls (Heasley et al., 2005). Elderly participants, irrespective of step height and visual condition,
spent significantly longer time in the anticipatory and weight transfer phases when stepping up to a new level than did the young adults (Heasley et al., 2014; Heasley et al., 2005). When vision was blurred, medial-lateral COM-COP divergence and medial-lateral COP displacement was more decreased in the elderly participants than in young (Heasley et al., 2005). The horizontal and vertical toe clearance (as the foot crossed the edge of the step during its forward swing) were also found to increase with blurred vision (Heasley et al., 2014), suggesting that individuals had difficulty identifying the edge of the step or perceiving the height of the step’s surface and increased foot-to-step clearances to provide a greater margin of safety (Heasley et al., 2014).

Taken together, these results suggest that under circumstances when vision is blurred, older adults use a twofold safety-driven adaptation to increase dynamic stability when ascending. Participants maintained a closer distance between the center of the base of support and the center of mass to maintain control while also increasing the horizontal and vertical toe clearance while swinging their front leg forward to reduce the risk of tripping (Heasley et al., 2014).

Buckley et al., (2005) also examined the effects of blurring vision being simulated by cataracts on medial-lateral balance during a single step down to a new level. The ground reaction force impulse in the medial-lateral direction was significantly greater when vision was blurred, while the average medial-lateral COM-COP distance was also considerably reduced with suboptimal visual information (Buckley et al., 2005). A greater lateral impulse permits individuals to shift their COM closer towards the stance limb during the single support phase to provide them with greater stabilization (Buckley et al., 2005). With blurred vision, the visual system is challenged to provide correct exteroceptive information. The resultant stepping movements become tentative, resulting in an average increase of 16.7% in the duration of double support. A corresponding increase in single support time was detected when vision was blurred, suggesting older adults emphasized additional caution when placing their lead limb on the
subsequent step (Buckley et al., 2005). Complementing these findings, during stair descent it has also been shown that at initial contact on the stairs, the COM acceleration variability in lateral direction was significantly greater in high-risk older adults with visual impairment in comparison to low-risk older adults (Zietz et al., 2011). Taken together, both findings add to the notion that movement control in the frontal plane deteriorates with increasing age, may result in increased hip and pelvis motion adding to instability, and increase likelihood of falling as vision is reduced (Zietz et al., 2011).

Because there is a paucity of literature investigating the impact of visual decline on balance control during stair ambulation, it is of interest to also include results reported when individuals navigate obstacles. Obstacle crossing is a widely studied mobility task which is similar to stair ambulation where an individual must clear the obstacle without contact. Novak & Deshpande (2014) manipulated visual (using simulated cataracts) and vestibular information during obstacle crossing with young and older adults. Measures of whole body and segmental control demonstrated increased COM displacement in the frontal plane with suboptimal vision for both older and young adults. Older adults also showed significantly greater trunk pitch and head roll angles under impaired vision conditions (Novak & Deshpande, 2014), highlighting a strong reliance on visual input but not vestibular information for locomotor control during obstacle crossing (Novak & Deshpande, 2014). Insufficient visual output may affect the ability to minimize anterior-posterior trunk movement despite a slower obstacle crossing time and walking speed; when combined with larger medial-lateral deviation of the body COM, this suggests the elderly may be at a greater risk for imbalance or inability to recover from a possible trip when clearing obstacles in their environment with insufficient visual information (Novak et al., 2014).
2.4.3 Effect of Lighting During Stair Ambulation

To date, there is limited literature examining the effect of lighting levels on balance control during stair ambulation, although the effect of lighting on foot trajectory variables has been investigated (Hamel et al., 2005). Hamel et al., (2005) examined the minimum clearance of the foot during stair descent with normal and low-level lighting. In response to a decrease in ambient lighting, young adults increased their average minimum clearance by 3.6 mm (Hamel et al., 2005). In comparison, older adults maintained the same clearance over all stairs (Hamel et al., 2005). Under both normal lighting and low lighting conditions, older adults also had significantly larger instances of minimum foot clearances which fell below 5 mm (Hamel et al., 2005). These results suggest that the inconsistency of minimum foot clearance, and absence of cautionary increases in foot clearance under reduced lighting, may contribute to falls on stairs by the elderly (Hamel et al., 2005).

It has also been shown that ability to detect stair edges can provide crucial visual cues for appropriate foot placement on the stair and for balance control during stair descent – particularly important when lighting is not optimal. Zietz et al. (2011) focused on both age and frailty-related changes in stepping parameters and COM control during stair descent and subsequently how these measures are affected by visual factors and lighting conditions. Older adults were split into two groups, based on low (n=7) and high (n=8) scores on tests of balance and balance confidence. A group of younger participants were also included. Kinematic data were collected from all participants while they descended stairs under varying visual conditions including both bright and dimmed ambient lights as well as both high and low stair edge contrast conditions (Zietz et al., 2011). Results showed that dimmed ambient lighting resulted in decreased step length, and reduced foot-to-step clearances, in the group of older adults with the highest tests on balance and stair confidence (Zietz et al., 2011). Furthermore, high stair edge contrast led to
reduced vertical COM acceleration variability in the higher functioning older adult group, and increased distance between COM and anterior base of support in the lower balance score group (Zietz et al., 2011). Based on the findings, the authors concluded that the differences in stepping behaviour shown by older adults in the higher balance score group may contribute to a higher risk of tripping. Further, the high edge stair contrast has a beneficial effect on balance control in older adults, as richer optic flow is provided and used to regulate balance (Zietz et al., 2011).

2.5 Stair Design and Falls

There are two main considerations for stair design, including (1) comfort and (2) safety for the user (Tutton & Campbell, 2013). With respect to the latter, safety initiatives focused on stair design aim to decrease the chance of falling on a stair and to minimize the severity of the injuries (Tutton & Campbell, 2013).

The tread depth- or horizontal surface of the stair- must support balance control (Novak et al., 2016), and be acceptable for the ball of the foot to land on the tread without ranging over the step below (Wright & Roys, 2005). By analyzing varying step geometry, kinematic data provided measures of segmental and whole-body dynamic control during stair descent (Novak et al., 2016) and the impact of changes in step riser heights and run lengths. When younger and older groups of adults descended a step of varying heights (7, 7.5 and 8 inches), results suggested that older adults maintained higher margins of stability than younger adults in the anterior-posterior direction because of their slower cadence (Novak et al., 2016). With both groups, however, longer run lengths were found to provide the largest margins of stability (Novak et al., 2016). It has also been shown that if there is insufficient placement or accommodation of the foot during stair descent due to a shorter step length, an over-step or misstep may occur, triggering a fall forward (Wright & Roys, 2005). In contrast, trips and falls during stairway ascent are often
credited to variation in riser, or vertical surface height (Cohen et al., 2009). Regardless of advances in knowledge of stairway safety, possibly hazardous stairway design practices seem to be widespread (Kim & Steinfeld, 2016). Many stairways are newly constructed with identifiable and well-known safety hazards that increase a person’s risk of tripping, slipping, or falling; often the staircases have features that clearly do not meet safety standards (Kim & Steinfeld, 2016). Recently, a scan of 578 stairways, identified in a popular architectural magazine over a thirteen-year publication period between 2000 and 2012, were ranked for railing, steps, visibility and other characteristics (Kim & Steinfeld, 2016). Sixty-one percent of the total number of stairways had at least one obvious design hazard and were classified as ‘hazard(s)-present’. The three most common design hazards were missing or inadequate handrails, excessive length of stairway flights, and low visual contrast on tread edges (Kim & Steinfeld, 2016).

To date, only one study has investigated user behavior on glass staircases - one of the architectural designs investigated within this thesis that may impact visual contrast of the step edge. Kim & Steinfeld (2014) surveyed user’s behavior and the incidence of unsafe stair use on a glass stairway in a retail store compared with a conventional stairway by documenting user behaviours (ie. handrail use, gaze behaviour, performance of secondary tasks), and stair incidents. Observations were conducted using a video recorder and a predefined checklist of behaviours (Kim & Steinfeld, 2014). Results demonstrated one incident of unsafe stair use (which may include for example a foot overstep or a slip) for every sixteen users who ascended/descended the glass stairway and one incident for every 136 users in the conventional stairway (Kim & Steinfeld, 2014). Authors hypothesized that walking on glass treads may be more dangerous than walking on conventional treads due in part to the reduced visibility the glass treads, and/or reduced friction between shoes and treads (Kim & Steinfeld, 2014).
Another important consideration regarding stair design is that of the open riser (Kim & Steinfield, 2016). It has been suggested that closed risers are preferred as they can prevent any accidental slipping under treads that may occur (Kim & Steinfield, 2016). The barrier between treads also block disrupting views in the background behind the stairway that may draw attention away from the travel path and can cause a misstep or a trip to occur (Kim & Steinfield, 2016). Open riser stairways can cause a person to feel a sense of uncertainty about the stair climbing task as visual distractions may be present underneath the stairs (Kim & Steinfield, 2016). Despite the suggested hazard associated with open risers, in addition to glass stairs, to date no study has comprehensively investigated the impact of such design practices on user behavior or balance control.
CHAPTER 3
RESEARCH AIMS AND OBJECTIVES

The primary purpose of the study was to investigate balance control when ambulating stairs of different architectural designs. Specific objectives addressed the primary purpose.

Study objective 1: To determine the effect of stair design and age on balance control under various lighting conditions with normal vision

Hypotheses:

- The glass stair condition and low lighting condition will result in reduced cadence and thus larger margins of stability
- Older adults will demonstrate larger margins of stability compared to young adults

Study objective 2: To determine the effect of stair design and age on balance control under various lighting conditions with blurred vision

Hypotheses:

- With blurred vision, older adults will reduce cadence compared to young adults
- The glass stair condition and low lighting will provide the greatest challenge to balance for both participant groups under the blurred condition
- Older adults will demonstrate decreased margins of stability and will position their COM further back from the step edge during stair descent compared to young adults
CHAPTER 4

METHODS

4.1 Study Design

This quantitative research study uses biomechanical measures to assess balance control during gait on stairs of various architectural designs (glass stairs, traditional wood stairs with open risers, and traditional wood stairs with closed risers).

4.2 Study Population

Healthy younger individuals (18-35 years of age) and healthy older, community-dwelling individuals (65+) participated in the study. Each group consisted of 16 individuals with a total of 32 participants. Participants were recruited from the community via recruitment flyers/newspaper ads and were also contacted through Toronto Rehab's volunteer subject database. Following initial contact, participants were screened via telephone (using a recruitment script) to ensure they met inclusion criteria. All participants were fully informed of the procedures involved of the study, and were asked to sign a consent form approved by the UHN Research Ethics Board prior to their participation. Risks related to their participation were described in the consent form, and participants were informed that it was possible to withdraw from the study at any time without consequence.

4.2.1 Inclusion and Exclusion Criteria

To be included in the study, all participants were community-dwelling, able to ascend and descend a flight of at least eight stairs independently (with or without handrail use) and presented with normal or corrected-to-normal vision. In addition, all participants were screened during initial contact with the researcher to exclude individuals with a history of vestibular
disorders, and/or cognitive deficits limiting communication, or if they present with neurological or orthopedic conditions (such as stroke, lower limb arthritis, or other relevant conditions) which affected their walking ability or balance. Participants needed to be able to understand instructions given in English as all the study documentation and instructions were delivered in English, including informed consent.

4.2.2 Sample Size Calculation

To date, no study has investigated similar conditions related to stair design to those of the current study. However, based on published data, Cohen effect sizes for significant findings ranged from .29 to .87 for measures of foot clearance between stair number (i.e. comparing top, middle, and bottom steps) when descending stairs (Hamel et al., 2005) and in margin of stability between age groups (Bosse et al., 2012). Similarly, based on published values, determined effect sizes between age groups ranged from 0.54 to 0.58 for relevant postural control measures including COM displacement and average pitch angle of the trunk (Novak et al., 2016). Based on these effects sizes and according to the calculations done with statistical software GPower3 it was determined that the total sample size will range from 12 to 64 individuals to determine significant differences between age groups, considering three levels of repeated measures (stair design condition: glass, wood closed risers, wood open risers). Type I error was set to an acceptable minimum ($\alpha = .05$) and a high level of power ($1 – \beta = .8$). Data were collected from a sample of 32 participants (16 per age group); thus, the final total sample size falls within the determined range, permitting detection of differences in the primary variables, while maintaining a realistic sample size for the project.
4.3 Experimental Environment

The study took place in the StairLab of the Challenging Environment Assessment Laboratory (CEAL) in Toronto Rehabilitation Institute. StairLab is a 5.55m x 5.15m modifiable laboratory space. StairLab included with a specially built glass tread staircase consisting of 8 steps: 2” thick x 36” wide x 12” long (0.05m x 0.91m x 0.30m), with a riser height of 8” (0.2m). The top landing of the staircase was 2” thick x 36” wide and 48” long (0.05m x 0.91m x 1.22m), which allowed a “turning station” at the very top of the stairs permitting an approach to accelerate during descent; participants were asked to approach the stairs from a distance back during ascent as well to ensure a similar acceleration was generated before beginning stair ascent. A removable wood cover was placed on top of each glass tread to create wood treads, and/or latched on the side of the stairs to create a closed riser. These removable wood covers permitted the comparison of user behavior on glass treads to other stair conditions such as open wood risers and closed wood risers (Figure 1). Two lighting conditions (normal bright light with a visual distraction, and low light with no visual distraction) were also created using a dimmer which was installed in the lab. Twelve motion capture cameras (Raptor-E, Motion Analysis Corp, California) were mounted throughout the laboratory environment to capture kinematic data at a recording frequency of 200 Hz. Finally, a visual distraction was placed beneath the stairs. This included a curved projection screen with a series of moving videos that were being projected on to it as individuals ambulated the stairs. The purpose of the distraction was to better simulate the effects of glass treads and open risers in the real-world, where people or other distractions are typically present and seen beneath the steps as individuals had to ascend and descend the stairs. Since this was the intention of the visual distraction, it was only present during the normal lighting conditions. For all testing, subjects wore a passive harness. The harness system permitted unrestricted walking on the stairs while protecting subjects from the
consequences of actual falls which may be experienced while walking and losing balance within
the laboratory environment.

![Figure 1. The three staircases designs: closed wood riser, open wood riser, and glass](image)

### 4.3.1 Testing Conditions

Individuals were asked to ascend and descend the glass treads under two visual conditions, two lighting conditions and three different architectural stair designs (stair condition). It should be noted that individuals ascended and descended the stairs without handrail use under all normal visual conditions and were asked to use the handrail when ambulating the stairs under the blurred visual condition. This protocol was chosen to increase ecological validity of the study as an individual with a visual impairment will prefer use of the handrail to ensure their safety and prevent any falls or missteps that may occur (Tromp et al., 2001).

Visual and lighting conditions were fully randomized within each stair condition to ensure fatigue or learning did not affect the results; the presentation of stair conditions was
blocked by stair condition within participants, but order of stair conditions was randomized between participants.

For the visual conditions, testing included: (1) normal vision and (2) suboptimal (blurred) vision. The blurred vision condition was created using custom-made blurring goggles which simulate the consequences of dense cataracts (Deshpande and Patla, 2007). These types of blurring goggles have been used in the past (Buckley et al., 2005; Heasley et al., 2005) and were created at a University Optometry school to ensure consistent sandblasting of the lens (Figure 2).

![Blurring goggles with sand-blasting of the lens](image)

**Figure 2.** Blurring goggles with sand-blasting of the lens

Lighting was manipulated to include two conditions: (1) bright light at 300 lx with a visual distraction and (2) low lighting condition at 3 lx with no visual distraction. The bright light at 300 lx represents the upper limit of civil twilight such as the type of lighting present in office buildings. The low lighting condition at 3 lx represents the lower level of civil twilight under a clear sky. To attain accurate and symmetrical lighting conditions between participants and stair conditions, a lux meter was used to measure the light.

For the three architectural stair designs, testing included: (1) closed wood riser, (2) open wood riser and (3) glass. These different architectural stair designs were created using removable
wood covers that were placed and latched on top of the glass treads (to create open wood risers) and wood covers latched on to the side to create closed risers. These covers were easily removable between the different trials (see Figure 1). Within each design condition, the order of testing was randomized for the intact vision, the blurred vision and the lighting conditions, across participants.

4.4 Participant Instrumentation

Reflective, motion capture markers were used to track whole body movement of the participants. Rigid clusters of three non-collinear markers were secured bilaterally to the feet, shanks and thighs. Clusters were also secured on the pelvis, upper thoracic region and on a band secured around the participant’s head. Additional markers were also placed over medial and lateral aspects of the ankle, knee, hip, around the pelvis (ASIS, PSIS, Greater Trochanter) and on the acromions to permit identification of joint centers and segment endpoints in a static standing position. These additional markers were removed for the walking trials. Markers were attached to participants with non-allergenic tape and with elasticized straps. Participants were asked to wear running shoes, covered in black tape to avoid unwanted reflections in the environment. Following completion of the walking trials, a pointed probe instrumented with reflective markers fixed relative to the tip was used to identify the segment endpoints of the feet. These virtual locations were tracked relative to a cluster of three reflective markers fixed to the participant’s shoes. Finally, the edges of the stair treads in the global coordinate system were also identified using the pointed probe.
4.5 Procedure

Data was collected in one session lasting approximately two hours. Informed consent, clinical (Timed Up and Go Test) and demographic (i.e. age, weight, height, frequency of stair use) data were obtained at the beginning of the testing session. The Timed Up and Go test provides a clinical measure of functional mobility status across participants (Podsiadlo et al., 1991). This clinical assessment determines the time that a person takes to rise from a chair, walk three meters, turn around, walk back to the chair, and sit down (Podsiadlo et al., 1991). The Timed Up and Go Test (TUG) was performed twice per participant and an average score was obtained. The Contrast sensitivity (Elliott et al., 1996) and Snellen Visual Acuity assessments (Elliott et al., 1996) were also measured for all participants under normal and suboptimal visual conditions.

Following completion of assessments and instrumentation, participants were asked to ascend and descend the glass tread staircase in a step over step manner at a self-selected speed. All participants completed three ascent/descent trials under every condition. A single handrail was present for all trials although participants were asked to not use the handrails unless required for the normal visual conditions (i.e. in the event they felt unstable and likely to fall) and to use the handrail for all testing completed under the suboptimal vision conditions. As previously described, participants also wore a passive harness for all testing. Two researchers were present in StairLab at all times with the individual to ensure the participant was comfortable with all testing procedures and remained safe while ascending and descending the stairs. Also, continuous feedback from the participants was encouraged so that any uncomfortable actions were immediately stopped. Participants were allowed rest breaks as needed throughout the data collection sessions.
4.6 Data Processing and Analysis

Kinematic data were collected using Cortex software (Motion Analysis Corp). Data was then analyzed using commercial biomechanical software (Visual 3D, C-Motion Inc) where a biomechanical model was developed and gait events during the stair gait cycle were identified (described in detail below).

4.6.1 Biomechanical Model

A three-dimensional, 9-segment, link-segment biomechanical model was developed using visual 3-D. Each segment was defined by appropriate distal and proximal endpoints. Segment definitions are provided in Table 1.

4.6.2 Identification of Gait Events

In the absence of force data to delineate the stair gait cycle and identify gait events, a previously validated method using segmental kinematics was applied (Foster et al., 2014). To define events during ascent and the descent, four event detection algorithms for defining touch-down and foot-off during stair descent and stair ascent using segmental kinematics were used (Foster et al., 2014). For stair descent, foot contact was defined as the vertical velocity minima of the whole-body center of mass, while, foot-off was defined as the instant of trail limb peak knee flexion (Foster et al., 2014). For stair ascent, vertical velocity local minima of the lead-limb toe were used to define foot contact, and foot-off was defined as the local maxima in vertical displacement between the toe and pelvis (Foster et al., 2014).
Table 1. Summary of the tracking markers, segments and endpoints used to create the biomechanical model

<table>
<thead>
<tr>
<th>Segment</th>
<th>Proximal joint</th>
<th>Distal joint</th>
<th>Tracking markers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot</td>
<td>Lateral malleolus</td>
<td>Centre point, front of shoe</td>
<td>Cluster of 3 reflective markers secured on shoe</td>
</tr>
<tr>
<td></td>
<td>Medial malleolus</td>
<td>(virtual point identified with</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pointed probe)</td>
<td></td>
</tr>
<tr>
<td>Shank</td>
<td>Lateral epicondyle</td>
<td>Lateral epicondyle</td>
<td>Cluster of 3 reflective markers secured mid-shank</td>
</tr>
<tr>
<td></td>
<td>Medial epicondyle</td>
<td>Medial malleolus</td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td>Greater trochanter</td>
<td>Hip joint center (defined</td>
<td>Cluster of 3 reflective markers secured mid-thigh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>using CODA method (Visual 3D ,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2016)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lateral epicondyle</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medial epicondyle</td>
<td></td>
</tr>
<tr>
<td>Pelvis</td>
<td>Point vertically above the</td>
<td>Right Hip Joint center</td>
<td>Cluster of 3 reflective markers secured on pelvis</td>
</tr>
<tr>
<td></td>
<td>greater trochanter, at the level</td>
<td>defined using CODA method</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of the ASIS</td>
<td>(Visual 3D , 2016)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Point vertically above the</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>greater trochanter, at the</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>level of the ASIS</td>
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<tr>
<td></td>
<td></td>
<td>Point vertically above the</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>greater trochanter, at the</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>level of the ASIS</td>
<td></td>
</tr>
<tr>
<td>Thorax</td>
<td>Right acromion</td>
<td>Left acromion</td>
<td>Cluster of 3 reflective markers secured on upper thorax</td>
</tr>
<tr>
<td>Head</td>
<td>Posterior marker on the right</td>
<td>Posterior marker on the</td>
<td>Band of reflective markers around participant’s head</td>
</tr>
<tr>
<td></td>
<td>side of head</td>
<td>left side of head</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anterior marker on the right</td>
<td>Anterior marker on the</td>
<td></td>
</tr>
<tr>
<td></td>
<td>side of head</td>
<td>left side of head</td>
<td></td>
</tr>
</tbody>
</table>
4.7 Outcome Measures

Stair ascent and stair descent were analyzed separately. All measures of interest were determined either at the instant of foot contact during the stance phase, or as the peak during the stance phase. When considering the latter (instant of foot contact), many falls during stair descent may be due to errors in foot landing such as over steps, thus, COM dynamics were important to analyze at this instant in time (Novak et al., 2016). Measures were calculated for both the second transition step and for the middle step of the staircase during steady state stair ascent and descent (Cluff & Robertson, 2011), as has been previously done (Novak et al., 2016). The second transition step was necessary to analyze rather than the first transition step because of limited marker presence at the very top and bottom of stairs (i.e. the cameras could not detect the markers), therefore the second transition step was instead included. For stair ascent, the onset of foot contact and toe-off was determined on the second transition step (second step from the ground) where the individual transitions from level walking and middle of the staircase for the steady state step. For stair descent, foot contact and toe-off was determined on the second transition step at the top of the staircase for the transition step and the middle of the staircase for steady state step (see Figure 3).
4.7.1 Postural Control Variables

Average cadence (number of steps/min) was determined for both stair ascent and descent. Metrics related to COM control were also determined. COM position is defined as the weighted average of the individual center of mass of the segments of the body (Winter, 1995). Balance control during gait is significantly reliant on the ability to control COM motion; the following balance control measures were determined for both ascent and descent:

- Medial-Lateral Range of the COM: Medial-Lateral (M-L) Range of the COM was quantified during transition and steady state gait as an indication of total body sway in the frontal plane. This was determined as the total range during the stance phase.
• Peak Medial-Lateral & Peak Anterior-Posterior COM Velocity: Velocity (m/s) is a vector expression of the displacement that an individual’s COM will undergo with respect to time (Adamczyk & Kuo, 2009). COM velocity provides additional information related to balance control beyond simply that of COM displacement. Specifically, the magnitude of the COM velocity within the displacement range may influence one’s ability to maintain balance (Pai & Patton, 1997). COM velocity was calculated as the peak velocity determined during the stance phase in both the medial-lateral (M-L) and anterior-posterior (A-P) directions.

Additional metrics calculated during stair descent only included:

• Margin of Stability (MOS): indication of center of mass control relative to the anterior boundaries of the base of support (step edge during descent). Note, margin of stability was not determined during ascent as the forward boundary of the base of support would not be as risky. Margin of Stability was calculated at an instant of foot contact as many falls during stair descent are thought to be triggered by errors during the foot landing such as oversteps, hence, COM dynamics are likely to be vital at this point in time (Novak et al., 2015).

Margin of Stability & sub-components of the MOS equation:

• The instantaneous distance between the extrapolated COM (XCOM) and the anterior boundary of the base of support in the sagittal plane (defined by the edge of the step when the foot was placed beyond the step edge) (Novak et al., 2016).

• The extrapolated COM includes a term (vCOM/√(gl-1)) which represents the COM displacement that would be required to arrest the COM motion in a dynamic situation (Novak et al., 2016).
• The XCOM is determined with the formula (Hof et al., 2005):

\[ XCOM = pCOM + \frac{vCOM}{\sqrt{\left( g \right)^{-1}}} \]

• pCOM is the anterior-posterior component of the vertical projection of the COM in the global coordinate system

• vCOM anterior-posterior velocity of the COM

• g: acceleration due to gravity

• l: distance between the COM and the ankle

4.8 Statistical Analysis

Descriptive statistics (means, and standard deviations were calculated as appropriate for all outcome measures. A two-sample t-test was used to determine significance of demographic variables (height, weight and Timed Up and Go scores) between participant groups.

Because the vision conditions (intact and blurred) were tested under different handrail conditions (ie. when ascending and descending with intact vision, participants did not use the handrail; when ascending and descending with blurred vision, participants used the handrail), comparisons including vision conditions were not possible given the possible confound of handrail use. Therefore, mixed factor ANOVAs were conducted for each dependent biomechanical variable of interest, separately for intact vision and blurred vision. Under both the intact (no handrail condition) and blurred vision (handrail condition) the mixed factor ANOVA included all main effects (age, lighting, design) and first-order interactions (age*lighting; age*design; design*lighting). Second-order interactions (age*light*design) were not considered as these interactions were less meaningful to addressing the study objectives. Following the identification of a significant main effect, post-hoc pairwise comparisons were conducted using Tukey's HSD adjustments to account for multiple comparisons. Where first-order interaction
effects were identified, only certain pairwise comparisons (those of interest to the primary objectives) were considered. For example, only pairwise comparisons of stair condition were considered within each age group (i.e. older adults on glass stairs differing from young adults on open wood stairs were not considered). All statistical analyses were conducted using SAS Version 5.2 Enterprise. A significance level of p <.05 was implemented for all analyses.
5.1 Demographics

Sixteen healthy younger adults (YA) (18-50 years old) and sixteen healthy older adults (OA) (over 65 years old) were recruited for the study. However, data analysis was restricted to 12 of the 16 younger adults and 14 of the 16 older adults. A total of six participants were excluded from the analysis due to problems with the data acquisition system and missing data. The prior sample size calculation was completed assuming effect sizes between age groups ranging from 0.54 to 0.58 to yield a total of 12 to 64 participants. Since we collected data from sixteen participants per group, with analysis performed on twelve from the younger adults and fourteen from the older adults, our sample size criteria were still met.

Participant characteristics are presented in Table 2. There were no significant differences in height (p>.297) or weight (p>.187) between groups. The older adults demonstrated significantly slower average TUG scores when compared to young adults (p=.011), although both groups completed the TUG test under the threshold defining functional mobility deficits (TUG score >12 seconds (Bischoff et al., 2003)).
Table 2. Participant demographics

<table>
<thead>
<tr>
<th>Demographics</th>
<th>Young Adults</th>
<th>Older Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>24.2 ± 3.7</td>
<td>69 ± 5.1</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>5/7</td>
<td>6/8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>173.5 ± 0.1</td>
<td>178.5 ± 0.5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.0 ± 15.6</td>
<td>86.0 ± 38.3</td>
</tr>
<tr>
<td>Hand dominance (R/L)</td>
<td>9/3</td>
<td>12/2</td>
</tr>
<tr>
<td>TUG score (seconds)*</td>
<td>7.9 ± 1.1</td>
<td>9.1 ± 1.2</td>
</tr>
</tbody>
</table>

**Normal Vision**

| Visual acuity, left eye               | 20/25        | 20/30        |
| Visual acuity, right eye             | 20/25        | 20/30        |
| Visual acuity, binocular             | 20/25        | 20/25        |
| Contrast sensitivity, left eye       | 1.5 ± 0.4    | 1.4 ± 0.2    |
| Contrast sensitivity, right eye      | 1.4 ± 0.5    | 1.4 ± 0.4    |
| Contrast sensitivity, binocular      | 1.6 ± 0.3    | 1.4 ± 0.3    |

**Blurred Vision**

| Visual acuity, left eye               | 20/30        | 20/50        |
| Visual acuity, right eye             | 20/25        | 20/50        |
| Visual acuity, binocular             | 20/30        | 20/50        |
| Contrast sensitivity, left eye       | 0.9 ± 0.4    | 0.7 ± 0.3    |
| Contrast sensitivity, right eye      | 0.9 ± 0.4    | 0.7 ± 0.3    |
| Contrast sensitivity, binocular      | 1.05 ± 0.3   | 0.8 ± 0.3    |

*indicates significance between groups, p<.05

5.2 Stair Ascent

5.2.1 Cadence

Under the normal visual conditions, no main or interaction effects of age (p=.46), lighting (p=.23) or stair design condition (p=.20) were found. Under the blurred visual condition, both groups of participants ascended stairs with a slower cadence under the low lighting condition compared to bright lighting (p=.001). There was also a significant main effect of the stair condition (p=.004). Slower cadence was found for the glass stair condition when compared to closed wood (p<.02) and open wood stair conditions (p<.008) for both groups, across both lighting conditions. Results are presented in Figure 4.
Figure 4. The average cadence (steps/min) during stair ascent for closed wood (black), open wood (grey) and glass stairs (dotted) across (A) normal vision and (B) blurred visual conditions. Standard deviation bars are depicted on the figures. * Indicates significant main effect of lighting. † Indicates significant difference between the stair conditions across both lighting conditions and both groups.

5.2.2 Medial-Lateral Range of the COM

When ascending the stairs under normal vision, the M-L range of the COM did not differ between lighting (p>.27) or stair conditions (p>.19), nor were any interaction effects determined (p>.33), for both the transition and steady state steps. M-L range of the COM also did not differ between age groups when ascending during steady state gait (p=.43). However, older adults demonstrated greater M-L range of the COM compared to young adults on the transition step during ascent under normal vision (p<.05).

Under blurred vision, increased M-L range of the COM was found in the low lighting compared to bright light condition (p=.001) when individuals ascended the transition step; older adults also demonstrated greater M-L range of the COM compared to young adults for both the transition and steady state steps (p<.03). No significant main effect of stair condition or interaction effects were found during blurred vision ascent for the transition (p>.56) and steady state steps (p>.62). Medial-lateral range of the COM is presented in Figure 5.
5.2.3 Peak Medial-Lateral COM Velocity

During ascent under normal vision, peak M-L COM velocity did not differ between stair conditions (p>0.12), lighting conditions (p>0.73) or age (p>0.13) for the transition and steady state steps. Similar non-significant effects were detected when ascending under blurred vision (p>0.21), with one exception. Individuals had an increased medial-lateral COM velocity in the low lighting condition compared to the bright light (p=0.02). Results are presented in Figure 6.
5.2.4 Peak Anterior-Posterior COM Velocity

When ascending the stairs under the normal vision condition older adults showed slower COM velocity in the anterior-posterior direction compared to young adults for both transition and steady state steps. Ascent on the glass stairs transition step also resulted in slower AP-COM velocity compared to the closed (p<.001) and open wood stair conditions (p<.0006). There was a group by stair condition interaction effect for the steady state step where glass stairs were different from the other two conditions within the young adult group only (p<.004).

Similar to ascent with normal vision, for the blurred visual condition under both the transition step and steady state steps a main effect of lighting (p<.001), age group (p<.05) and stair conditions (p<.001) was detected. Older adults consistently demonstrated a slower AP-
COM velocity across all conditions (p<.02). The low lighting condition also yielded slower AP-COM velocity compared to bright light (<.0001). Additionally, all individuals displayed slower AP-COM velocity when ascending the glass stair condition under both lighting conditions when compared to ascent during the closed wood and open wood stair conditions (p<.01). Peak anterior-posterior COM velocity results are presented in Figure 7.

Figure 7. The peak anterior-posterior COM velocity (m/s) during stair ascent for closed wood (black), open wood (grey) and glass stairs (dotted) across normal vision (top) and blurred visual conditions (bottom) and across transition step (left) and steady state step (right). Standard deviation bars are depicted on the figures. All values were taken from touchdown to foot-off. Positive values represent forward velocity. * Indicates significant main effect of lighting. † Indicates significant difference between the stair conditions across both lighting conditions and both groups. β Indicates significant main effect of age. ŵ Indicates group by stair condition interaction effect where glass stairs are different from the other two stair conditions within the young adult group only.
5.3 Stair Descent

5.3.1 Cadence

Under normal vision, both older and young adults demonstrated reduced cadence when descending the glass stairs compared to the closed wood (p<.001) and open wood stair conditions (p<.0001).

Under the blurred visual condition, cadence was also significantly less for descent on the glass stairs compared to the open wood stair condition (p=.009). Participants also demonstrated reduced cadence when descending stairs under low light compared to bright light conditions when vision was blurred (p<.001). Cadence during descent is shown in Figure 8.

Figure 8. The average cadence (steps/min) during stair descent for closed wood (black), open wood (grey) and glass stairs (dotted) across normal vision (left) and blurred visual conditions (right). Standard deviation bars are depicted on the figures. * Indicates significant main effect of lighting. † Indicates significant difference between the stair conditions across both lighting conditions and both groups.

5.3.2. Medial-Lateral Range of the COM

Medial-Lateral range of the COM is presented in Figure 9. When descending the stairs with normal vision, M-L range of the COM did not differ between lighting conditions (p=.77), stair conditions (p=.36), or age groups (p=.14) for the transition step (p>.14). In contrast, when descending the steady state step, an increased M-L range of the COM in the low lighting
condition was detected when compared to stair descent under bright light (p<.001). Individuals also demonstrated an increased M-L range of the COM when descending the glass stairs compared to the closed and open wood stair conditions (p<.009).

Under the blurred visual condition, a main effect of lighting (p<.008) was detected for both the transition and steady state steps, where all individuals had an increased M-L range of the COM in the low lighting condition compared to the bright.

Figure 9. Medial-lateral range of the COM (m) during stair descent for closed wood (black), open wood (grey) and glass stairs (dotted) across (top) normal vision and (bottom) blurred visual conditions and across (left) transition step and (right) steady state step. Standard deviation bars are depicted on the figures. * Indicates significant main effect of lighting. ƚ Indicates significant difference between the stair conditions across both lighting conditions and both groups.
5.3.3 Peak Medial-Lateral COM Velocity

During stair descent, no significant main effects of age (p>.14), lighting (p>.50), or stair condition (p>.07), nor interaction effects, were detected for medial-lateral COM velocity under both normal vision and blurred vision walking conditions.

5.3.4 Peak Anterior-Posterior COM Velocity

The peak COM velocity in the anterior-posterior direction only differed between stair conditions when both groups descended the transition step under normal visual conditions (p<.001). During this time, individuals displayed a decreased peak AP-COM velocity for the glass stairs compared to closed wood (p<.0001) and open wood conditions (p<.02). A significant main effect of lighting was also seen, but restricted to blurred vision conditions, during steady state stair descent (p<.05), where individuals demonstrated a decreased AP-COM velocity under low lighting compared to bright light conditions. Peak AP-COM velocity during the stance phase is shown in Figure 10.
Figure 10. Peak anterior-posterior COM velocity (m/s) during stair descent for closed wood (black), open wood (grey) and glass stairs (dotted) across (top) normal vision and (bottom) blurred visual conditions and across (left) transition step and (right) steady state step. Standard deviation bars are depicted on the figures. All values were taken from foot contact to foot-off. Positive values represent forward velocity. * Indicates significant main effect of lighting. ƚ Indicates significant difference between the stair conditions across both lighting conditions and both groups.

5.3.5 Margin of Stability

When descending the stairs with normal vision, all individuals had larger margins of stability in the glass stair condition compared to the closed wood (p<.008) and open wood (p<.0001). Older adults also displayed a larger margin of stability across all conditions compared to the younger adults (p<.01).

When vision was blurred, similar to normal vision, glass stairs presented with larger margins of stability compared to descent on open wood and closed wood stair conditions (p<.0098). A group-by-light interaction effect also showed that young adults had larger margins of stability under low lighting compared to bright light (p<.0001) when descending the transition and steady state steps. Margin of stability is presented in Figure 11.
Figure 11. The margin of stability (m) at foot contact during stair descent for closed wood (black), open wood (grey) and glass stairs (dotted) across (top) normal vision and (bottom) blurred visual conditions and across (left) transition step and (right) steady state step. Standard deviation bars are depicted on the figures. All values were taken from the onset of foot contact. A positive margin of stability indicates postural stability. A negative margin of stability indicates the XCOM exceeds the boundaries of the base of support. * Indicates significant main effect of lighting. † Indicates significant main effect of stair condition across both lighting conditions and both groups. ß Indicates significant main effect of age. ð Indicates significant group-by-light interaction effect, where low light differed from bright light for the young adult group only.

5.3.6 Anterior-Posterior COM Position Relative to Step Edge at Foot Contact

The position of the COM relative to the step edge in the anterior-posterior direction was determined at the instance of foot contact during stair descent, as one of the components of the margin of stability equation, to assist with understanding differences found in the margin of stability.

COM in the A-P direction was positioned further back from the step edge for older adults compared to younger adults under normal visual conditions for the transition (p<.045) and steady state steps (p<.029). When descending the stairs with blurred vision, a significant effect of stair condition was found for the steady state steps only (p<.001), but no significance of lighting or age was found (p>.14). Post hoc analyses revealed the COM was positioned further behind the step edge during stance phase when descending glass stairs compared to the closed wood (p<.006) and open wood (p<.001) stairs. Results are presented in Figure 12.
5.3.7 Velocity of the COM at Foot Contact

The velocity of the COM (vCOM) at the instance of foot contact was also determined, as the other component contributing to the margin of stability equation, to assist with understanding differences found in the margin of stability. Under both normal and blurred visual conditions, the vCOM at the instant of foot contact during descent significantly differed between stair conditions (p<0.036), which was true for both transition and steady state steps; Individuals had a faster vCOM in the closed and open wood compared to the glass stair condition. Younger adults also had increased vCOM compared to older adults when descending the steady state step under
normal vision (p=.04). Finally, both groups demonstrated faster vCOM in the bright light condition compared to the low light when descending under blurred vision (p<.0001); no significant effect of lighting was found under the normal vision conditions. Velocity of the COM results are presented in Figure 13.

Figure 13. Anterior-posterior velocity of the COM at foot contact (m/s) during stair descent for closed wood (black), open wood (grey) and glass stairs (dotted) across (top) normal vision and (bottom) blurred visual conditions and across (left) transition step and (right) steady state step. Standard deviation bars are depicted on the figures. All values were taken from the onset of foot-contact; positive represents forward velocity of the COM. *Indicates significant main effect of lighting. ƚ Indicates significant difference between the stair conditions across both lighting conditions and both groups.  البعض Indicates significant main effect of age.
CHAPTER 6
DISCUSSION

This is the first study to comprehensively evaluate balance control during stair ambulation on stairs of different designs (glass stairs, wood stairs with open-risers, and wood stairs with closed risers). Results revealed older adults had larger margins of stability at foot contact in the anterior-posterior direction compared to younger adults when vision was normal and position their COM further back from the step edge during descent compared to young adults. However, older adults also demonstrate greater frontal plane motion during ascent when compared to young adults. Under the low lighting conditions with suboptimal vision, both groups displayed a slower COM velocity in the sagittal plane during ascent and descent. Under the most challenging conditions (blurred vision, low lighting), the young adult group also demonstrated larger margins of stability, whereas the older adults did not adopt a larger margin of stability in response to these same conditions. Both groups, however, displayed larger margins of stability during the glass stair condition compared to the other two architectural designs. This was due to a COM that was positioned further back from the step edge at foot contact combined with reduced COM velocity when descending the glass stairs compared to the other architectural designs.

6.1 Compensatory Strategies Are Adopted During Ambulation on Glass Stairs

The use of unique architectural designs when building stairs in public and private environments is becoming more common (Prismma, 2015). To date, only one study has compared glass staircases to a conventional wooden staircase using qualitative observations of stair users in a public environment. Their results demonstrated that participants were much more cautious when ambulating glass staircases and as such directed their general gaze towards the steps more frequently (Kim & Steinfeld, 2014). Despite this, more incidences of unsafe stair use
were noted on the glass staircase. Results of the current study support those of Kim & Steinfeld (2014). When ascending glass stairs (under blurred vision only) and when descending stairs under both vision conditions, young and older adults reduced their overall cadence, likely as a compensatory measure in response to the challenge of ambulating on the glass stairs. In the case of stair descent, this slower cadence adopted by our participants resulted in larger margins of stability when descending glass stairs compared to the open-wood and closed-wood stair design conditions. Additionally, individuals displayed a slower anterior-posterior velocity of the COM at the initiation of foot contact when descending the glass stairs. It has been previously shown that people reduce walking speed to improve walking stability (Arif et al., 2004; Menz et al., 2003). Decreased velocity may signify an effort at increasing postural stability to reduce fall risk (Schinkel-Ivy et al., 2015). Specifically, decreased velocity may reduce the body’s momentum, increasing the likelihood of recovering from a loss of balance should one occur (Schinkel-Ivy et al., 2015). It has also been shown in the literature that walking performance is affected by both physiological and psychological factors (Delbaere et al., 2009) and the relationship between balance confidence and walking velocity has been established with older adults (Delbaere et al., 2009; Schinkel-Ivy et al., 2015). For example, when walking on a raised platform, under conditions of postural threat where there are greater levels of concern about falling, larger alterations in walking speed and the related measures of step length and double support time have been shown (Delbaere et al., 2009). Although we did not explicitly measure confidence or perceptions of safety when ambulating each staircase, our results suggest that individuals may have interpreted before even beginning to ambulate the stairs that glass staircases are unsafe with potential loss of balance confidence, therefore making global adjustments in speed, and resultant stability margins, to compensate for the increased risk of sustaining a fall on the glass stairs.
Despite the larger stability margins adopted in the sagittal plane, glass stair treads still presented with increased sway in the frontal plane under normal vision when compared to the other architectural designs. Increased medial-lateral movement has been shown in other stair descent studies (Novak et al., 2016) and has implications for fall risk; particularly for older adults given declines in physiological capacities which affect ability to counter movement in the frontal plane (Novak et al., 2016).

6.2 Impact of Open Riser Staircase

Another important stair design consideration is that of the open riser (Kim & Steinfeld, 2016). Open risers may also be an issue in the built environment and have been flagged as such by the accessibility community. To address this concern, the building code states that openings shall be of a size which will prevent the passage of a sphere having a diameter more than 200 mm (Building Code, 2006). Open riser construction is becoming a versatile option and can be used across many staircase styles, incorporated into both straight and curved staircases for interior and exterior projects (Artistic Stairs, 2017). However, open riser stairways can cause a person to feel a sense of uncertainty about the stair climbing task as visual distractions may be present underneath the stairs during ascent; During descent, an open riser has been suggested as a safety concern as the user does not have a cue from the solid back riser to guide foot trajectory and may present a hesitant or variable gait leading to a fall (Kim & Steinfeld, 2016). To date no study has comprehensively investigated the impact of such design practices on user behavior or balance control. Although we found no differences with our current measures between the open riser and closed riser staircase (or our control staircase), this may be due to the type of open-riser design used in this study, where individuals did not perceive it to be risky. Alternatively, additional biomechanical fall risk measures such as foot trajectory or foot placement variability
may help to understand more comprehensively the impact of open risers on fall risk and further research is needed.

6.3 Age-Related Differences in Balance Control during Stair Ascent and Descent

It is well-established that older adults fall significantly more than young adults during stair walking (Scott et al., 2010). Measures of balance control may provide some insight into the underlying reasons for the increased fall risk with age.

The margin of stability was only determined for stair descent, as it provides an indication of center of mass control relative to the anterior boundaries of the base of support – i.e. the step edge during descent; during ascent, the forward boundary of the base of support would not present to be as risky. The results of this study are consistent with other studies (Novak et al., 2016) where older adults were reported to have larger margins of stability at foot contact in the anterior-posterior direction compared to younger adults when vision was normal. The margin of stability is dependent on many variables; in this study (as has also been shown previously (Novak et al., 2016), older adults position their COM further back from the step edge compared to young adults. However, these findings have not been consistently reported in the literature (Bosse et al., 2012). Bosse and colleagues (2012) showed that older individuals have a reduced capacity to control the body’s COM during stair descent, a result of a higher COM velocity and more anterior position of the vertical projection of the COM (Bosse et al., 2012). The conflicting results may be explained by the apparatus used- in the latter study, a 3-step staircase was used. In the current study, individuals walked down an 8-step staircase which may have presented as a larger challenge, thus, demanding a more conservative approach to stair descent to minimize fall risk and maximize safety. It is interesting to note that older adults did not adjust cadence or margins of stability compared to their younger counterparts when vision was blurred. This lack of compensatory adjustment could result in increased risk of falls for the older group under more
challenging vision conditions. Despite a conservative approach to stair descent in the sagittal plane to improve safety, during ascent, the older adults generally demonstrated greater COM range in the frontal plane compared to young adults. It has been previously shown that increased COM accelerations in the medial-lateral direction with older adults support a decline in frontal plane movement control with increasing age. The additional frontal plane movement causes augmented hip and pelvis motion adding to instability and increased likelihood of falling (Zietz et al., 2011). Ascent also requires concentric demand from the muscles to raise the body to the next step up (Novak et al., 2010). With age, muscle strength decreases (Reeves et al., 2009), resulting in older adults utilizing a greater proportion of their maximal muscle capacity to ascend stairs (Reeves et al., 2009). This could be a contributing factor to the increased sway noted in the frontal plane with age, which has the potential to increase risk of mis-stepping during ascent.

Our data also revealed that when ascending the stairs under both normal and blurred visual conditions, peak A-P COM velocity was significantly slower in older adults compared to young. These findings support other studies, where age-related adaptations in the stair ascent strategy was detected. Older adults lower the peak force requirements of limb extensor muscles (Mian et al., 2007) to reduce the A-P COM acceleration and avoid a forward fall (Zietz et al., 2011). Although older adults positioned their COM further back behind the step edge during the stance phase, similar age-related differences in COM velocity were not seen during stair descent. These finding are particularly important for older adults because the total body mass must be controlled during stair descent. Age-related changes in neuromuscular function (Novak et al., 2016) may challenge an older adult’s ability to counter the high COM velocity and forward momentum of the upper body, therefore potentially increasing the likelihood of a fall (Novak et al., 2016).
6.4 Low lighting Impacts Balance Control

It is well established that sufficient vision is an important factor contributing to safe walking (Zietz et al., 2011), and fall prevention programs consistently identify proper lighting in stairwells as a simple intervention to reduce fall risk (Zietz et al., 2011). When presented with low ambient light levels, greater demands on balance control for all individuals were evident in this study, further highlighting the importance of lighting levels for safe stair ambulation. In general, both young and older adults reduce cadence in response to low lighting, but only when blurred vision was also present. These findings are consistent with other studies (Heasley et al., 2005). Heasley et al., (2005) observed that when vision was blurred, older adults took 11% longer to execute stepping, requiring additional planning time to ensure a fall does not occur. In our study, only with the additional challenge of the blurred vision combined with low lighting did participants demonstrate a global response to slow down during both ascent and descent. It may be that participants did not perceive a task challenge with low lighting alone, but when together, the vision decline affected the capability to precisely judge the step dimensions in the travel path (Vale et al., 2008) and additional global compensations were made.

When ascending the stairs, low lighting did not significantly affect balance control in the frontal plane when vision was intact, although increased M-L range of the COM and increased medial-lateral COM velocity was found in the low lighting compared to bright light condition for the transition step only with suboptimal vision. In contrast, results showed that when descending the stairs, an increased M-L range of the COM in the low lighting condition was detected when compared to stair descent under bright light, which is seen regardless of whether vision is intact or blurred. These findings highlight the challenge of stair descent compared to ascent, particularly in the frontal plane, and the role sufficient lighting plays to support balance. It should be noted that when descending with blurred vision, individuals were instructed to use a
handrail. Handrail use has been shown to improve medial-lateral stability due to several factors, including perceived stability and/or increased proprioceptive cues (Zietz et al., 2011). Despite the feedback afforded by the handrail, low lighting resulted in increased medial-lateral sway when vision was suboptimal. It has been shown that age-related deterioration in contrast sensitivity is worsened with low illuminance (Tang & Zhou, 2009). The current findings emphasize the importance of proper lighting to support balance control in the frontal plane for individuals with vision decline, even in the presence of a handrail. Interestingly, when both groups ascended and descended the stairs, low lighting yielded slower COM velocity in the sagittal plane compared to bright light, but only when vision was blurred. The young adult group also demonstrated safer margins of stability during stair descent with blurred vision and low lighting. As previously discussed, under the blurred conditions, individuals were instructed to use the handrail to assist with balance and demonstrated reduced cadence, likely in response to the challenge of the task, thus a reduction in COM velocity under these conditions is reasonable. Unlike young adults, however, older adults did not adopt a larger margin of stability in response to low lighting with blurred vision. Although not significant, older adults had slightly higher margins of stability compared to young adults in general with blurred vision, which may have played a role in the findings (i.e. the older group already adopted large margins of stability and did not adjust gait in response to low lighting when vision was blurred). Alternatively, the lack of compensatory adjustments in response to the challenging lighting conditions with blurred vision during stair descent may highlight the increased risk of falls in the older adult group. Similar findings have been shown with older adults when assessing foot-to-step clearances under similar conditions during stair walking (Hamel et al., 2005). Further research is needed to elucidate the role the handrail and cadence differences played in the results when lighting was dimmed, and vision was suboptimal.
CHAPTER 7
LIMITATIONS

7.1 Study Limitations

The current study is subject to several limitations. Firstly, the staircase used was an 8-step, straight run staircase, with analysis restricted to the initiation of foot contact and toe-off for the first transition step and a single steady-state step. Forensic evaluation of stair falls has shown that many stair-related falls will occur on short-rise staircases (3 steps and under), or staircases with winders (for example). Longer staircases, such as with 12 or more steps, are also commonly found in the home (Cohen et al., 2009). These longer staircases may result in greater physical demands and fatigue for certain users, impacting balance control. This study was also completed in a controlled lab environment, and as such may not fully replicate a real-world scenario as the lab environment/harness may influence normal walking patterns (individuals may feel safer, for example, because they were wearing the harness); in real-world situations, many individuals using the staircases simultaneously, or other environmental distractions, may influence one’s balance control. In addition, cadence was not controlled for in this study and individuals walked at a self-selected pace. In a real-world setting, individual’s will not always be able to adjust gait (i.e. slow down) in the presence of risk and this would presumably affect margins of stability outside of a laboratory environment. Blurred and normal vision were also unable to be compared due to handrail use. Under normal visual conditions participants did not use a handrail during stair ambulation while under the blurred visual conditions, participants used a handrail. Finally, each stair descent was preceded by a previous stair ascent which could be a potential limitation as fatigue and adaptability may have impacted our results.
CHAPTER 8
FUTURE DIRECTIONS

8.1 Relevance of Findings

This research addressed an important knowledge gap regarding stair design, by understanding balance control on stairs with different architectural designs under varying visual conditions (intact vision and blurred vision), changing ambient light levels and the impact of aging. Results demonstrate that, in general, individuals are adopting compensations (i.e. slowing down) in response to perceived risk or actual risk during stair descent on glass treads. These compensations suggest a higher risk associated with ambulating glass stairs compared to the other stair designs evaluated in this study. Our findings are in line with observational studies which have identified glass stairs to be a risky design choice in the environment. In addition, with low ambient light levels, greater demands on balance control for all individuals were evident in this study, further highlighting the importance of lighting levels for safe stair ambulation.

The results from this study will ultimately inform best practice design recommendations for reducing stairway missteps and falls. It is important to quantify behaviour during stair ambulation considering new up-to-date stairway designs and how specific characteristics can contribute to the risk of falls during stair locomotion.

8.2 Future Work in the Field

Future work should build on our findings associated with balance control to investigate additional biomechanical risk factors (such as foot control variables) and provide a more comprehensive analysis of architectural stair design during both stair ascent and descent. Consideration of persons with mobility impairment and other orthopedic conditions that can affect walking ability to should be included in future work to broaden the scope of the research.
Finally, future investigations should consider ambulation with a longer flight of stairs (i.e. up to 13 steps, which are common in-home staircases) or biomechanical risk in “real-world”, outdoor settings, where additional distractions and multiple people ambulating the stairs at the same time would presumably further impact balance control and risk of falls.
CHAPTER 9

CONCLUSIONS

As hypothesized, the glass treads and low lighting condition without the visual distraction had the greatest demands on balance control during normal vision and blurred visual conditions. This was reflected by individuals adopting compensations to increase safety, such as reducing their cadence, positioning COM further from step edge and decreasing their velocity of the COM, in response to perceived risk or actual risk during stair descent on glass treads and during the low lighting conditions. It should be highlighted that this thesis is not a recommendation for the installment of glass treads as might be interpreted through the presence of larger stability margins with this stair design. While the results do show larger margins of stability in the anterior-posterior direction, this may not actually translate to “safer” stair walking, and in fact does not – particularly because individuals slowed down on glass treads meaning they anticipated possible risk. The glass treads and the low lighting condition also showed greater sway in the medial-lateral direction – despite slowing down in expectancy of risk, this does not necessarily mitigate medial-lateral risk. In a real-world environment, individuals are likely to be less cautious when ambulating stairs than in our controlled laboratory environment, with multiple distractions present. Future studies should aim towards evaluating similar balance control measures in the “real-world” to gain an even better understanding of potential risk of ambulating different architectural stair designs.
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