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# The effects of glass stairways on stair users: An observational study of stairway safety

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ABSTRACT

The purpose of this study was to assess the safety of a winding glass stairway by observing the behavior of stair users and to identify issues that should be studied in a laboratory setting. A checklist for coding stair use behaviors was developed. Video observations were conducted in a retail store with a glass stairway (GS) and a shopping mall with a conventional stairway (CS). Key behaviors related to safety (tread gaze, diverted gaze, handrail use) and stair incidents on the two stairways (GS and CS) were identified from the recordings and compared. On the glass stairway, more users glanced down at the treads (GS: 87% vs. CS: 59%); fewer users diverted their gaze away from the stairs (GS: 54% vs. CS: 67%); and handrail use was higher (GS: 32% vs. CS: 24%). Incident rates were much higher on the glass stairway (6.2%) compared to the conventional stairway (0.7%). Walking on winding treads made of glass may be more dangerous than walking on conventional materials due to reduced visibility of the tread edge or reduced friction between shoes and treads. Recent laboratory research suggests that stairway users may behave more cautiously using stairways with glass treads but the results from this study demonstrate that the benefit of increased caution can be negated in real world conditions.

## 1. Introduction

Stairway falls are clearly a public health concern. Each year in the U.S., about 1,300,000 hospitalizations and 2,100 deaths are caused by stair-related injuries (National Safety Council, 2015). The annual cost of stair-related injuries is the largest contributor to product injury costs ($92 billion dollars), followed by injuries due to floors and home furnishings (Lawrence et al., 2015). While the majority (90%) of falls occur in home settings (Pauls, 2013), the fall risk is equally problematic in public buildings where it represents a major source of injury claims, e.g., in workplace, retail, and leisure environments (Cohen, et al, 2009; Templer and Archea, 1983; Templer, 1992). Danford et al. (2009) found that using stairways was the most problematic activity reported by respondents in an online survey. Stairway use is also a cross-disability issue since it involves mobility, perception, and cognition (Archea et al., 1979; Templer, 1992). Thus, creating usable and safe stairways should be a top priority for the building industry. Knowledge for the appropriate design of stairways is limited, however, which has resulted in difficulty developing best practices and improving design guidelines and building codes. In the absence of definitive knowledge, contemporary architects are experimenting with unusual stairway designs, including the use of glass treads, which may increase a person's risk of tripping, slipping, or balance problems. In a study on trends in stairway design practices, a high proportion of unsafe stairway designs were constructed, in contradiction to best practices and even in clear violation of building codes and standards (Kim and Steinfeld, 2016).

This study is part of a larger investigation of stairway safety, which includes a literature scan of design practices (Kim and Steinfeld, 2016), additional observational studies (Kim and Steinfeld, 2014) and laboratory research (Boyaninska, 2018; Novak et al., 2016). A winding stairway in a popular retail store was selected for the study because it has unusual design conditions that may increase the risk of falls; these include a winding stair configuration, open risers, and glass treads. Winding or spiral stairways are considered to be more dangerous than straight stairways because the treads are tapered so that users must twist their bodies and shift their weight differently on the left and right foot while climbing the stairway (Steinfeld and Maisel, 2012). The risk of losing balance is higher compared with straight treads which do not require users to rotate their center of gravity while traversing the stairway (Archea et al., 1979). In addition, people tend to stay to the right on stairways in the U.S., therefore the effective tread depth is different going up than down on winder treads. When stairs curve upward in the clockwise direction, people tend to climb up the steps along the inner radius where the tread is narrower and descend along the

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outer tread that is wider. When the stairs curve upward in the anticlockwise direction, people ascend at the wider end of treads and descend at the narrower end.

Furthermore, open risers can create distracting conditions, particularly in the unblocked views of customers, merchandise and external light sources behind the stairway during ascent (Kim and Steinfeld, 2016). Although research suggests winder treads increase perceptions of risk and vigilance behavior on stairs (Templer, 1992), the design and context of glass stairways may cause users to divide their attention between looking at the stairs itself and the surrounding environment, more than they would otherwise do so.

Stairway use is also affected by the tread material. Glass may reduce visibility and detectability of tread edges and thus increase the likelihood of the user to misjudge steps and misstep. Although non-slip treatments are available for glass walking surfaces, where users are likely to track water in during bad weather, these treatments may not be adequate because water is not absorbed by glass; water on treads may therefore negate the effect of "non-slip" coatings and textures and cause loss of traction and friction between shoes and treads. The last problem was clearly known to the managers of the store studied. Carpeting is installed on the glass treads and landings on days with heavy precipitation.

Since little is known about the impact of glass stairways on user safety, the purposes of this study was to investigate the effects of glass stair treads on behavior and safety by comparing the effects to the use of conventional stair treads and to identify issues that should be studied further in a more controlled laboratory setting.

The following hypotheses guided the research:

- **H1:** Walking on glass treads will increase tripping, slipping or balance problems in stair walking compared to walking on treads constructed from conventional materials.
- **H2:** Diversions of attention away from stair treads will lead to more serious consequences on glass stairways than on conventional stairways.

## 2. Methods

### 2.1. Site selection

A retail store stairway in New York City was chosen as the study site for observations of behavior on a glass stairway. A stairway in a Buffalo area shopping mall was identified as the comparison site (Fig. 1). The two stairways had similarities and differences. Both were prominent, highly visible, monumental feature stairways with many users. The glass stairway had fifteen risers in each of four flights between intermediary landings that wrapped completely around a glass elevator shaft (a full 360 degrees) in an upward anticlockwise direction. The conventional stairway had seven risers that ascended clockwise in a quarter-turn (90 degrees) configuration. The conventional stairway was longer but each flight was about half the length of one flight of the glass stairway and the radius of the turn was much larger, which reduced the difference in tread depth (running) across the length of the tread. Contrast marking stripes were present only on the first and last step of each flight of stairs in the glass stairway. There were no contrast marking of treads in the comparison site (see Table 1).

**Table 1**
Profile of stairway characteristics.

| | Glass Stairway (GS) | Conventional Stairway (CS) |
|---|---|---|
| Configuration | Circular | Quarter-turn |
| Views from the stair (available on both sides of the stairs and directly ahead) | Yes | Yes |
| Contrast marking on tread edges | First and last step of each flight | No |
| Tread depth (inner) | ~11 in (280 mm) | 10.25 in (260 mm) |
| Tread depth (outer) | ~1′–8″ (508 mm) | 13 (330 mm) |
| Riser height | ~6 in (152 mm) | ~6 in (152 mm) |
| Handrail width | 1.5 in (38 mm) | 1.5 in (38 mm) |
| Number of flight(s) observed | 2 | 2 |
| Location of observed flights | First bottom flight | First 2 bottom flights |
| Riser count (top flight) | n/a | 7 |
| Riser count (bottom flight) | 15 | 7 |

### 2.2. Data collection

Video recording was selected as the study method because recordings could be replayed repeatedly for analysis purposes. It has also been used in prior studies of stair incidents (Templer et al., 1978; Archea et al., 1979; Cohen, 2000), although earlier studies were limited due to the technological constraints and high costs of video recording at the time, as well as the intrusiveness of the process. Today, overt recording in public places is generally acceptable due to the ubiquitous use of electronic devices with video capabilities. Recording devices are also much smaller and less conspicuous.

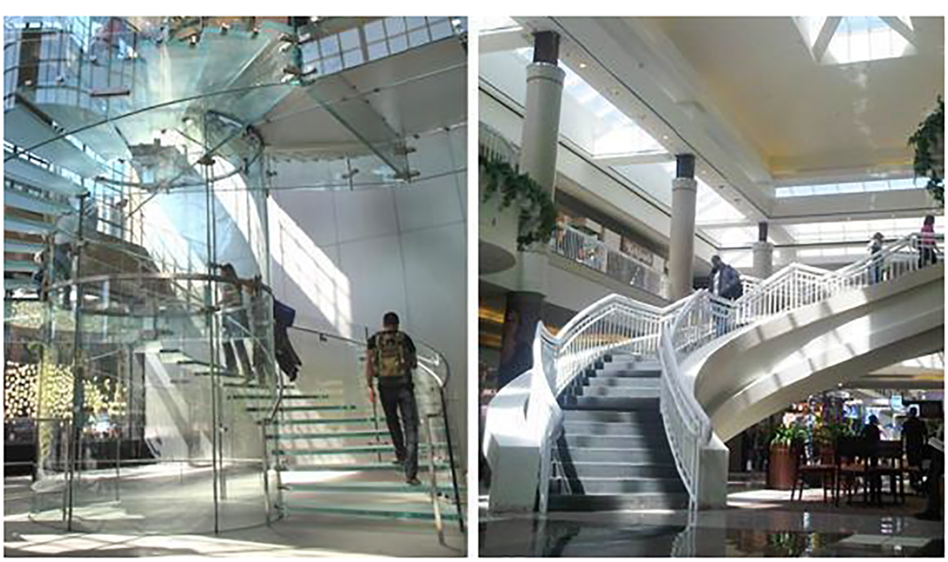

**Fig. 1.** Glass stairway (GS) made of glass stair treads at a retail store (left); Conventional stairway (CS) made of concrete stair treads at a shopping mall (right).

The University Institutional Review Board (IRB) determined that our research did not meet the definition of research with human subjects. The settings were public and we did not obtain any personal information about people through intervention or interaction, therefore no IRB approval was needed for the project.

Prior to the implementation of this research, a pilot study was conducted in a glass stairway to determine the feasibility of direct observations of stair users using video recording and to confirm areas of unsafe stair use for further investigation. All data on stair users' characteristics, behaviors, and incidents were recorded on a preliminary checklist, coded and analyzed using a computer-based video processing program. During this process, stair use incidents that indicated potential safety problems were extracted from the video recordings and time-stamped so that incidents could be located easily for further analysis. The data provided strong evidence of unsafe stair use and were judged suitable for detailed analysis. The video clips were reviewed by colleagues who concurred that a controlled comparison study would be more fruitful than a single case study to identify patterns of stair use that could be attributed to the unique design of the stairway in the retail store. Thus, a comparison site with a conventional stairway that had winders was identified and an additional set of data was obtained from similar observations.

Video recordings of stair use were collected by the first author at the retail store on a Saturday and Sunday, both very busy times for the store, between 12:00 and 15:00 on two separate weekends using the same method as the pilot study. Video recordings were collected at the shopping mall on a Monday and Saturday during the afternoon, also a busy time. At each site, the video recorder was positioned to capture images of stair users from head to foot. The observer sat with the recording device in a seating area within 20 feet of the stairway. Only descending users were observed due to limitations of camera angles that make it difficult to observe people ascending in the opposite direction. Observations were also limited to the bottom two flights of stairways or the portion of the stairs visible from the camera's point of view. As with the pilot study, all data on stair users in descent were recorded on a checklist that was developed for the final study—the Stairway Observation Checklist (SOC).

### 2.3. Stairway Observation Checklist (SOC)

The Stairway Observation Checklist (SOC) was developed to categorize stair users' behaviors and characteristics (Fig. 2). The SOC included information on demographics (apparent age and gender), key safety-related behaviors, other behaviors, and stair use incidents. Stair incidents included hesitation, balance loss, and missteps which, in this study, are considered "precursors of falls." Hesitation refers to any interruption in gait flow that delays, confuses or impedes action. Balance loss refers to body sway relative to the floor that cause the user to depart from a natural upright posture, with the exception of body sway due to obvious health conditions. Missteps are any awkward placement of the foot on treads and can take many forms, e.g., air step, heel scuff, overstep, slip, trip, and understeps.

Tread gaze, diverted gaze, and handrail use are key behaviors important for using stairways safely. Stair research clearly demonstrates that where stair users look, or the direction of their gaze, is important for safety, particularly whether it is towards the treads or elsewhere. Additionally, whether the handrail is used or not by the user is typically observed in stair safety studies since it is the main safety device.

Tread gaze, or observed glances at treads, is important for depth perception, foot placement (Archea et al., 1979; Miyasike-daSilva and McIlroy, 2012) and postural control (den Otter et al., 2011). Depending on how safe the stairway appears to the user, tread gaze occurs either frequently or infrequently and can be measured by the number of gazes per steps taken, e.g. once every seven steps taken (Templer, 1992). For safe negotiation of stairway runs, one glance may be necessary at the beginning, middle, and end phases of stair walking, or the transitions and middle steps of a flight of stairs (Miyasike-daSilva and McIlroy, 2012). Thus, frequent tread gaze was defined as glancing at the treads three or more times throughout an entire flight of stairs, and infrequent tread gaze as two or less times. Tread gaze was measured each time the user's head turned downwards toward treads.

Diverted gaze denotes the user's gaze orientation turning away from the stairs. In previous studies, videotapes of actual accidents show that missteps and accidents often occur when people divert their gaze away from the stairs (Archea et al., 1979; Templer et al., 1978).

Handrail use improves stability and suggests that the user perceives a need for postural support, as seen in studies of elderly people negotiating stairways (Hamel and Cavanagh, 2004). Although handrail use is generally low (30%), the presence of handrails can help to reduce the severity of falls (Cohen and Cohen, 2001). This is especially important for people at higher risk of falling.

## 3. Results

### 3.1. Analysis

Data analysis was conducted using two hours of data selected at random from original sets of video recordings made at each site. The rates of behaviors and incidents were calculated and compared between the two stairway sites. Behavior rates were calculated by counting the total number of times the behavior occurred and dividing by the total number of users. Incident rates were calculated by dividing the total number of stair incidents by the total number of users, a method used in previous studies (Templer et al., 1978).

The *t*-test corrected for unequal variances (Welch test) was conducted to determine whether the means of behaviors and incidents between the GS and CS sites were statistically significant. Chi-square tests (cross tabulations) were conducted to analyze the associations between (1) behaviors and stair sites and (2) incidents and stair sites. Correlations of age and gender were also examined. All of the statistical tests were conducted using a 0.05 alpha level.

### 3.2. Demographics

A total of 531 users were observed at the GS site and 545 users at the CS site. More men were observed in the GS site (56.3%) than women. More women were observed in the CS site (61.1%) than men. A majority of adults were observed at GS (80.4%). At CS, most of the users were adults (57%) and young adults (31%). Table 2 presents the differences in demographics between the GS and CS sites.

### 3.3. Safety behaviors

Table 2 also presents the safety behavior rates at the GS and CS sites. The *t*-tests conducted on the safety behaviors revealed statistically significant differences in stair use. More stair users glanced down at the winding treads made of glass than the winding treads made of conventional material (GS: $M = 0.872$; CS: $M = 0.593$, $p < .001$). Fewer stair users diverted their gaze away from the glass stairway (GS: $M = 0.539$; CS: $M = 0.666$, $p < .001$), which may explain the higher rates for tread gaze. When returning attention to the stairway, users may have a tendency to re-orient themselves by glancing at the stairs. Handrail use was higher in the glass stairway (GS: $M = 0.322$; CS: $M = 0.244$, $p = .005$). The result supports research findings that show handrail use is often minimal in stair use. Fig. 3 shows the cross-site comparison of the key safety behaviors.

Age is a risk factor in stair research. The two stair sites were statistically significant on age ($p < .001$) and gender ($p < .001$). In GS, age was significantly correlated only to diverted gaze ($p = .020$). In CS, age was significantly correlated to only handrail use ($p = .034$). The greatest usage exposure and injury rates are for young adults (Pauls, 2011). For children and older adults, the potential risk of falling is

| Location: | | | | | | Date: | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Observer: | | | | | | Start and End Time: | | | | |
| | Stair Users | | | | | | | | | |
| **Age** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | ... |
| Child (age 1-14) | | | | | | | | | | |
| Young Adult (age 15-24) | | | | | | | | | | |
| Middle-Aged Adult (age 25-64) | | | | | | | | | | |
| Older Adult (age 65+) | | | | | | | | | | |
| **Gender** | | | | | | | | | | |
| Female | | | | | | | | | | |
| Male | | | | | | | | | | |
| **Key Safety Behaviors** | | | | | | | | | | |
| Frequent tread Tread gaze (≥3 glances at treads) | | | | | | | | | | |
| Infrequent tread Tread gaze (≤2 glances at treads) | | | | | | | | | | |
| Diverted gaze | | | | | | | | | | |
| Handrail use | | | | | | | | | | |
| **Other Behaviors** | | | | | | | | | | |
| Talking | | | | | | | | | | |
| Using electronic devices | | | | | | | | | | |
| Carrying things | | | | | | | | | | |
| **Stair Incidents** | | | | | | | | | | |
| Hesitation | | | | | | | | | | |
| Balance loss | | | | | | | | | | |
| Misstep | | | | | | | | | | |

**Fig. 2.** Stairway Observation Checklist (SOC).

**Table 2**
Demographics and stairway behavior characteristics.

| | GS (N = 531) | | CS (N = 545) | | Chi-square p value |
|---|---|---|---|---|---|
| | % of sample | n | % of sample | n | |
| **Age** | | | | | |
| Child | 3.0 | 16 | 8.6 | 47 | |
| Young adult | 12.4 | 66 | 31.0 | 169 | |
| Adult | 80.4 | 427 | 57.0 | 311 | |
| Elder | 4.14 | 22 | 3.3 | 18 | |
| **Gender** | | | | | |
| Female | 43.7 | 232 | 61.1 | 333 | |
| Male | 56.3 | 299 | 38.9 | 212 | |
| **Safety behaviors** | | | | | |
| Tread gaze | 87.2 | 463 | 59.3 | 323 | < .001 |
| Diverted gaze | 53.9 | 286 | 66.6 | 363 | < .001 |
| Handrail use | 32.2 | 171 | 24.4 | 133 | .005 |
| **Stair incidents** | | | | | |
| Hesitation | 4.1 | 22 | 0.2 | 1 | < .001 |
| Balance loss | 1.7 | 9 | 0.4 | 2 | .032 |
| Missteps | 0.4 | 2 | 0.2 | 1 | .550 |
| Total incidents | 6.2 | 33 | 0.7 | 4 | < .001 |

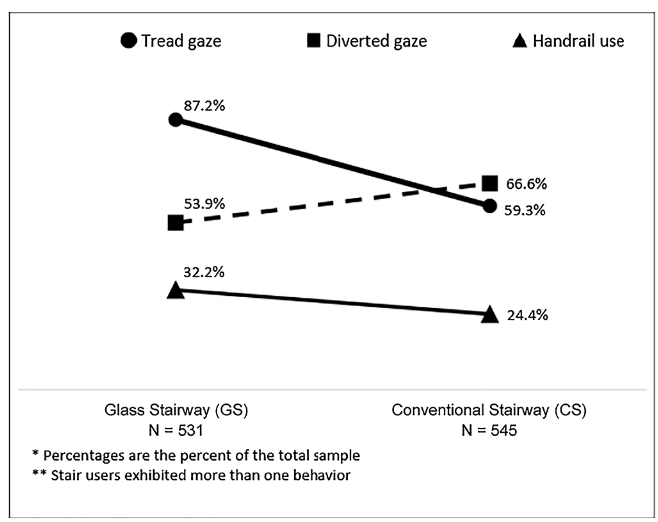


**Fig. 3.** Cross-site comparison of key safety behaviors.

higher due to developmental characteristics and aging processes.

Gender was significantly correlated to both diverted and tread gaze behaviors across the two sites (all p values were less than .001). In GS, diverted gaze was higher in men (66.5%, 199). In CS, tread gaze was higher in women (71.7%, 239). Handrail use was not correlated to gender in either site (GS, $p = .688$; CS, $p = .644$). Gender was not found to be significantly correlated to incidents across the sites. Although the literature indicates that there are no significant differences in accident rates between men and women, the risk is generally higher for men in the workplace and higher for women in home settings (Templer, 1992).

In the glass stairway, about 1.5% (8) of the stair users descended to their left side where the treads were wider. This behavior was not observed at CS.

### 3.4. Incidents

The total incidence of gait errors as a percent of all stair descents on the glass stairway was 6.2% (33) compared to 0.7% (4) on the conventional stairway (see Table 2). This result was significant (GS: $M = 0.06$; CS: $M = 0.01$, $p < .001$). Thus, one incident was likely to occur for every 16 users in the GS, and one incident was likely for every

**Table 3**
Gaze behaviors during incidents across stair sites.

| Gaze behavior | GS (n = 33) | | | CS (n = 4) | | |
|---|---|---|---|---|---|---|
| | % of incidents | n | Chi-square p value | % of incidents | n | Chi-square p value |
| Tread gaze | 63.6% | 21 | $< .001$ | 25% | 1 | .162 |
| Diverted gaze | 72.7% | 24 | .025 | 100% | 4 | .155 |

136 users in the CS. Users of the GS were eight times more likely to have an incident.

Hesitation was observed at an incidence of 4.1% in the glass stairway compared to 0.1% in the conventional stairway, $p < .001$. Balance loss was the second most frequent stair incident in GS (1.7%) while it occurred in CS at less than half that rate (0.3%), $p = .032$. The rate of missteps in GS was observed to be twice the rate of CS, although not statistically significant, $p = .550$.

Strong correlations were found between the behaviors and incidents at the GS site. A strong, negative correlation was found between hesitation and tread gaze (GS, $p < .001$; CS, $p = .228$). Balance loss also had a strong, negative correlation with tread gaze (GS, $p = .004$; CS, $p = .790$) and handrail use (GS, $p = .037$; CS, $p = .422$). A positive correlation was found between hesitation and diverted gaze (GS, $p = .034$; CS, $p = .479$).

In GS, tread gaze of three or more glance frequencies occurred in 63.6% of the incidents, $p < .001$, and diverted gaze occurred in 72.7% of the incidents, $p = .025$. Table 3 shows an analysis of the gaze behaviors during incidents at the two sites. In GS, incidents occurred with a higher tendency for both tread and diverted gaze. In CS, more stair incidents occurred with infrequent tread gaze (75%). Diverted gaze was observed in every stair incident in CS (100%, 4). The gaze behaviors in CS were not found to be statistically significant; this is likely due to the low number of incidents that were observed.

## 4. Discussion

### *4.1. Visibility factors*

The first hypothesis proposed that walking on glass treads will increase stairway incidents compared to conventional treads, which was confirmed in this study. Users were observed to use the glass stairway more cautiously by gazing more frequently towards treads, gazing less towards their surroundings, and using handrails more, suggesting the glass stair treads were perceived as more dangerous by users. The tactile or visual quality of glass may actually transmit cues that some users perceive as evidence of danger. The findings also suggest users did not accurately perceive the glass stairway even with greater incidences of tread gaze. This finding contradicts the common view that increased visual scanning of treads improves user perception of stair conditions. Visibility of glass treads in either foveal or peripheral vision may have been difficult for the users. For example, in one video clip, a user approaching for ascent is gazing at the treads when his leading foot swings forward and hits the edge of the first step. Although research shows that contrast tread markings can increase visibility of stairs (Foster et al., 2014; den Brinker et al., 2005), little is known about its application for glass stairways. In particular, contrast tread markings are not required by building code regulations for the design of monumental feature stairways, such as the retail store stairways, although they often serve as a primary means of access to building and facility spaces. Further research is needed to confirm the visibility effects of glass treads and the implications for glass stairway construction in public buildings. Despite the more cautious behavior of stair users on the glass stairway, the incident rate was higher, demonstrating that caution cannot always overcome faults in stairway design.

There were significant effects of the glass stairway (GS) on safety-related behaviors, i.e., increased tread gaze, decreased diverted gaze, and increased handrail use. In particular, diverted gaze was found to be associated with incidents ($p = .025$), suggesting that diverted gaze led to missteps. But this association was not found to be significant in the CS site ($p = .155$). The results indicate that visual scanning differences in the two retail stores were a contributing factor to the increased stair incident rate, which lends support to the second hypothesis. Users gazed at the treads more frequently and used handrails more often in the GS; but, diversion of attention appears to have negated the increased effort of users to be safe due to the effects of the winding glass stair design. Video analyses revealed that the first four steps of the bottom or top of stair flights were locations prone to missteps; stair users were observed to divert their gaze away from the stairs toward the adjacent views of the store. In one video clip, a user is ascending at the bottom of the stairs and looks to his right towards the interior of the store when he under-steps the fourth tread and nearly falls. This effect was also observed at the middle of the stairs where the steps turned toward the same views as described above. This finding is consistent with research that shows higher rates of incidents at the top and bottom of stair flights (Templer et al., 1978) and on the steps that expose users to different views, e.g., “orientation edges” (Archea et al., 1979; Templer and Archea, 1983). The tendency to look around orientation edges towards interesting views can disrupt the subconscious monitoring of gait, particularly at critical points on the stairs, and this can trigger an accident (Archea et al., 1979). More attention is needed on how to design stairways in relationship to adjacent attractive features and views of the surrounding environment from the stairs. Since winding configurations continuously expose users to new views as they ascend or descend, visual distraction by surroundings may be a more serious problem on winders than on straight or switch back stairways. It is noteworthy that the GS turned through 360 degrees as compared to 90 degrees on the CS, which increases the speed and amount of information the user must process during ascent or descent. Research should also focus on how to make glass tread edges visible to an inattentive user's peripheral vision (Sloan, 2011), and how to encourage use of handrails to maintain balance if a misstep occurs (Maki et al., 2011).

### *4.2. Direction of stair curvature*

The study results also suggest that the direction of stair curvature was another design factor that contributed to the rate of incidents. Since the treads were narrower in descent on the right hand side in the retail store, overstepping or slipping off treads is a higher risk factor (Roys and Wright, 2005) compared to the conventional stairway that spiraled in the opposite direction. For example, in a video clip from the retail store observations, a user wearing boots and holding the handrail is gazing downwards as she lowers her left foot onto the first tread. The landing foot shifts inwards and the user stumbles towards the handrail. This incident could have been caused in part by low friction between the user’s boots and glass tread due to the shoe sole material, but the direction of stair curvature also appeared to alter stair use behavior. Some users were observed to be confused while descending along the inner, and narrower, end of the glass stairway. Such behaviors were rarely observed at the comparison conventional stairway site. For some people, the preferred way of using the stairway rising in the anticlockwise direction was to use the left side for descent (wider tread depth), even though this path created conflict with others who were ascending while staying to their right, as is the convention in the U.S. In one video clip from the glass stairway observations, an elderly user descending to her left with a cautious gait (and holding onto the handrail) is repeatedly forced to let go of the handrail and move aside for ascending traffic on the same side of the stair. A winding stairway rising in the clockwise direction would make descending along the conventional path more acceptable and safer for users (Templer, 1992). Stairway design should consider the differences in gait between users.

These complex gait differences include slower walking speed, shorter stride length, variation in shoe material and any unusual gait due to health conditions, particularly among people with physical or cognitive conditions who may have experienced a loss of skills to avoid slips and falls (Lockhart et al., 2009; Christina and Cavanagh, 2002). Studies comparing the winding direction but controlling for all other conditions would be useful to clarify the effect of stair curvature on incident rates.

### 4.3. Surface texture

There are some potential risk factors in the use of glass walking surfaces of stairways related to the material's slip resistant properties. Although existing codes, regulations, and consensus standards address the need for slip-resistant walkways, it may be difficult to accurately determine the actual risk of slipping. Slip resistance is a complex phenomenon that is not only dependent on the walking surface material, its frictional properties, footwear material and their frictional properties, but also on the method used to test slip resistance. The current national standard for walkway safety, the ANSI/NFSI B101 Standard, uses a method of measuring dynamic coefficient of friction (CoF) under wet conditions to determine the level of fall risk and level of traction (low, medium, high). This is in contrast to earlier methods that have relied on a single static CoF value measured under dry conditions, including ASTM-C10, a method withdrawn by ASTM. Wet dynamic CoF readings are considered to be a more appropriate measurement since stairway use involves constant movement and the majority (80%) of slips and falls occur on wet floors (Kendzior, 2011). Tribometers are used to measure the CoF of a material. Two industry standards, ANSI A137.1 and ANSI/NSFI B101.3 specify the use of a BOT-3000 tribometer to measure dynamic CoF. But Powers et al. (2010) demonstrated that widely different results can be obtained with different tribometers and the BOT-3000, among others, was found to provide unreliable results. Moreover, winding stairway configurations may require a different level of slip resistance because users must negotiate turns while traversing the stairway; thus the traction demand may differ from walking in a straight line (Templer, 1992). Further, most slips occur when people make turns or change directions in walking, which is not taken into consideration in many slip resistance test methods (Nemire et al., 2016). Glass stairways in public buildings should be in compliance with standards to protect owners, material manufacturers and architects from liability claims (Troyer, 2012). But, determining the CoF of a sample material in a laboratory may not provide a reliable indicator of slip resistance in the field, particularly if the measurement is a static test taken on dry material. Even industry standards that utilize testing under wet conditions do not necessarily provide reliable measurements if the tribometer used produces unreliable measurements, and, there is a real question whether they provide realistic evaluations of materials as they may be experienced in the field.

### 4.4. Limitations and directions for future research

This study had some important limitations. The first is the difference in the two stairway designs. The most significant differences were the construction materials, the winding direction and the radius of curvature. It is possible that the winding direction and curvature difference could have played a larger role in the results than the materials. Comparing stairways that share all but one similar feature would provide more direct comparisons but it is difficult to find such clear comparisons in the field. A second limitation is the videography method. Video camera angles did not allow the observer to watch a user continuously for the full length of winding flights. Thus, the study is probably underreporting incident rates. Simultaneous observations at both the bottom and top of winding flights would provide a fuller description of stair use. The videography method also did not allow accurate assessments of age and gender. The method used provided approximations of age and gender with the potential for some inaccuracy. Further studies of this type are clearly needed to improve upon methods and also to obtain benchmark data on the incidence of risky behaviors across a large sample of stairways. With benchmark data, the degree of risk posed by any one stairway could be assessed statistically.

Another limitation is that the study used naturalistic observations rather than laboratory experiments in which technologies such as eye-tracking or motion analysis can be employed. On the other hand, the video recording and checklist method enabled us to analyze and report stair use behaviors in naturalistic settings simply by tracking user movements, e.g., head, hands, and feet. The study method demonstrated that video recording is an inexpensive and easy way to study stairway safety in the field with large numbers of people. The study findings on behavioral differences in relation to different stairway designs led to a further investigation of the use of glass stair treads in a laboratory setting by our research collaborators (Boyaninska, 2018). Laboratory studies with controlled conditions and more sophisticated data collection tools are very valuable to control for the many variables existing in contemporary buildings, including visibility of surroundings with lots of activity and variations in slip resistance. However laboratory research has its own limitations like the expense of building stairways and recruiting and running large samples.

Boyaninska (2018) examined three architectural stair design conditions (glass treads, open wood risers, and closed wood) and compared balance control on two groups of participants under experimental conditions of normal and blurred vision/low light. The results showed compensatory strategies were adopted during ambulation in the more challenging conditions including blurred vision, low lighting, and glass stair treads. When descending the glass stairs under both vision conditions, young and older adults reduced their overall cadence which resulted in larger margins of stability (Boyaninska, 2018). Additionally the individuals displayed a slower velocity of the center of mass (COM) at the initiation of foot contact when descending the glass stairs (Boyaninska, 2018). Although she only studied a short straight stairway configuration, her results have implications for evaluating the slip resistance for winding glass stair treads since slower walking speeds while making turns may result in different traction demands as compared to faster cadence on straight stairways (Nemire et al., 2016). Designers need to consider how stairway configuration and user ability affect the dynamics of gait while using stairways rather than relying solely on tests of CoF using industry standards to determine the safety of a material. The laboratory research demonstrated that when encountering treads made of glass, stair users initiate compensatory actions and adapt learned behaviors (Boyaninska, 2018). This indicates that they perceived underlying risk. But, the field research suggests that if the tread edge design, stairway configuration or surroundings reduce visibility of the tread edge, cause alterations of gait, or distract attention, the impact of increased caution is negated.

## 5. Conclusion

Stair safety can be improved by increasing awareness of the many issues affecting trips, slips and balance problems on stairways. To our knowledge, this was the first study that compared the use of glass stairways with conventional stairways in everyday use. Our focus on a contemporary stairway design differed from previous studies on stair safety that have focused on traditional design and material of stairways. The results indicated that traversing winding stairs with glass treads may be more dangerous than traversing such stairs with conventional treads, due to reduced visibility of glass edges, reduced friction between shoes and treads and/or exposure to distracting influences in the surroundings. The study provides new insight into the effects of glass stair treads on the user's behavior and safety, however, further studies of other glass stairways are needed to clarify the results, particularly with respect to compensatory behaviors and the degree of impact CoF has on safety in real world conditions. The research technique used in this study can be used to evaluate the impact of other contemporary stairways in the field in order to obtain more knowledge about the safety of innovative stairway design features that are difficult to simulate in laboratory conditions.

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## References

Archea, J., Collins, B.L., Stahl, F.I., 1979. Guidelines for Stair Safety. U. S. Dept. of Commerce National Bureau of Standards, Washington.
Boyaninska, I.V., 2018. Balance control when ascending and descending stairs of different architectural designs (unpublished master's thesis). University of Toronto, Toronto, Ontario, Canada.
Christina, K.A., Cavanagh, P.R., 2002. Ground reaction forces and frictional demands during stair descent: effects of age and illumination. Gait Posture 15 (2), 153–158.
Cohen, H.H., 2000. A field study of stair descent. Ergonomics Des. 8 (2), 11–15.
Cohen, J., Cohen, H.H., 2001. Hold on! An observational study of staircase handrail use. In: Proceedings of the Human Factors & Ergonomics Society Annual Meeting, pp. 1502–1506.
Cohen, J., LaRue, C.A., Cohen, H.H., 2009. Stairway falls. Prof. Saf. 54 (1), 27–32.
Danford, G.S., Grimble, M., Maisel, J., 2009. Benchmarking the Effectiveness of Universal Design. The Architectural Research Centers Consortium, San Antonio, Texas.
den Brinker, B.P.L.M., Burgman, L.J., Hogervorst, S.M.J., Reehorst, S.E., Kromhout, S., van der Windt, J., 2005. The effect of high-contrast marking of treads on the descent of stairways by low-vision people. Int. Congr. Ser. 1282, 502–506.
den Otter, A.R., Hoogwerf, M., Van Der Woude, L.H., 2011. The role of tread fixations in the visual control of stair walking. Gait Posture 34 (2), 169–173.
Foster, R.J., Hotchkiss, J., Buckley, J.G., Elliott, D.B., 2014. Safety on stairs: influence of a tread edge highlighter and its position. Exp. Gerontol. 55, 152–158.
Hamel, K.A., Cavanagh, P.R., 2004. Stair performance in people aged 75 and older. J. Am. Geriatr. Soc. 52 (4), 563–567.
Kendzior, R.J., 2011. The new B101.1 floor safety standard. Occup. Health Saf. 80 (9) 36, 38, 40.
Kim, K., Steinfeld, E., 2014. The effects of interactive stairways on user behavior and safety. Assistive Technol. Res. Ser. 35, 157–166.
Kim, K., Steinfeld, E., 2016. An Evaluation of stairway designs featured in architectural record between 2000 and 2012. Archnet-IJAR 10 (1), 96–112.
Lawrence, B.A., Spicer, R.S., Miller, T.R., 2015. A fresh look at the costs of non-fatal consumer product injuries. Injury Prevent.: J. Int. Soc. Child Adolescent Injury Prevent. 21 (1), 23.
Lockhart, T., Kim, S., Kapur, R., Jarrott, S., 2009. Evaluation of gait characteristics and ground reaction forces in cognitively declined older adults with an emphasis on slip-induced falls. Assistive Technol. 21 (4), 188–195.
Maki, B.E., Sibley, K.M., Jaglal, S.B., Bayley, M., Brooks, D., Fernie, G.R., Zettel, J.L., 2011. Reducing fall risk by improving balance control: development, evaluation and knowledge-translation of new approaches. J. Saf. Res. 42 (6), 473–485.
Miyasike-daSilva, V., McIlroy, W.E., 2012. Does it really matter where you look when walking on stairs? Insights from a dual-task study. PLoS ONE 7 (9), e44722.
National Floor Safety Institute (NFSI), n.d. ANSI/NFSI B101.3 Test Method for Measuring Wet DCOF of Common Hard-Surface Floor Materials. Retrieved from < https://nfsi.org/ansinfsi-standards/standards/ > .
National Safety Council (NSC), 2015. Injury Facts, 2015 ed.
Nemire, K., Johnson, D., Vidal, K., 2016. The science behind codes and standards for safe walkways: changes in level, stairways, stair handrails and slip resistance. Appl. Ergon. 52, 309–316.
Novak, A.C., Komisar, V., Maki, B.E., Fernie, G.R., 2016. Age-related differences in dynamic balance control during stair descent and effect of varying step geometry. Appl. Ergon. 52, 275–284.
Pauls, J., 2011. Injury epidemiology. Paper presented at the International Conference on Stairway Usability and Safety, Toronto, Canada, June 2011.
Pauls, J., 2013. The pathology of everyday things – stairways – revisited. Proceedings of Annual Meeting of the Human Factors and Ergonomics Society, San Diego.
Powers, C.M., Blanchette, M.G., Brault, J.R., Flynn, J., Siegmund, G.P., 2010. Validation of walkway tribometers: establishing a reference standard. J. Forensic Sci. 55–2, 366–370.
Roys, M., Wright, M., 2005. Minor variations in gait and their effect on stair safety. In: Contemporary Ergonomics. Taylor & Francis, New York, NY, pp. 427–431.
Sloan, G.S., 2011. Perception & cognition. Paper presented at the International Conference on Stairway Usability and Safety, Toronto, Canada, June 9–10.
Steinfeld, E., Maisel, J., 2012. Universal Design: Creating Inclusive Environments. John Wiley & Sons, Hoboken, N.J.
Templer, J.A., Mullet, G.M., Archea, J., Margulis, S.T., 1978. An Analysis of the Behavior of Stair Users. NBSIR 78-1554. National Bureau of Standards, U.S. Department of Commerce, Washington, D.C.
Templer, J., Archea, J., 1983. Stairway Design for Reducing Fall Injuries in Industry. Georgia Institute of Technology, Pedestrian Research Laboratory.
Templer, J.A., 1992. The Staircase: Studies of Hazards, Falls, and Safer Design. MIT Press, Cambridge, Mass.
Troyer, D.D., 2012. New standards change the landscape of walkway safety. Occup. Health Saf. J. 81 (9) 48, 50.