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A Review of the Biomechanics of Staircase Descent: Implications for Building Fire Evacuations

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Abstract

Movement on stairs is a crucial factor that influences people's ability to evacuate from buildings in fire emergencies. In fact, the accessibility of stairs during multilevel evacuations is considered to be a criterion for the tenability of a building. Biomechanical analyses of pedestrian staircase descent add nuance by characterizing factors relevant to safe movement on stairs, such as foot placement, use of handrails, and balance. While these factors are not traditionally captured by evacuation analyses and models, their inclusion can point to areas of particular risk during evacuation from physiological, environmental, design, and engineering standpoints. This systematic review presents relevant biomechanical aspects, with a particular focus on factors that influence downward movement on stairs for evacuation purposes. The review begins with findings on walking speeds, gait analysis (e.g., cadence and foot clearance), as well as changing demographics are summarized. Then, research on balance control (vision, proprioception, and limb coordination) is presented, followed by findings on fatigue and grasping. Implications of the empirical findings are then considered for evacuation modelling, safer and more efficient evacuation procedures, as well as building design. Finally, limitations of the review itself and future research needs are explored.

Keywords: biomechanics, egress, evacuation, stair descent, staircase descent

1 Introduction

Walking down stairs is not a trivial task, especially in emergency conditions. Staircase[1] evacuation during fire is a complex task that can be associated with unexpected obstacles that need to be avoided (e.g., due to debris and damaged stairs), suboptimal viewing conditions (i.e., emergency lighting) and environmental hazards, particularly smoke. Negotiating staircase descent involves the intersection of human factors, including visual ability and mobility, and the ergonomic design of the staircase itself. This literature review focuses on the biomechanics[2] of staircase descent as it relates to evacuation.

1.1 Evacuation via stairs

Movement on staircases is an especially important consideration for evacuation, due to the fact that elevators are typically not available for use [2], [3]. Occupants are often considered to be trapped in the building if the stairs become untenable [4], [5] . Consequently, movement capabilities on stairs have been cited as a determinant of successful evacuation.

Staircase evacuation can be described in terms of collective walking speeds of occupants, density of people on staircases and landings, and occupant flow (i.e., the number of evacuees passing through a certain point over time). Compared to level walking, staircase evacuation is comparatively slower because of the descending movement and the merging behaviours of people entering the staircase from different floors [6]–[8]. Not surprisingly, people with mobility impairments typically have slower walking speeds and evacuation times [9]–[11]. This is often true even when assisted by firefighters, staff or a stair descent device [10]. Indeed, Kuligowski et al. [10] compared the speeds of older adults (categorized as 65 years or older) based on their level of required assistance. With the exception of those assisted by firefighters who moved significantly slower and those who had no disabilities and moved slightly faster, they found comparable speeds amongst the other older individuals, who had significantly slower speeds. Accordingly, those with lower than average walking speeds can reduce the walking speeds for

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[1] Note on terminology: A *stair* is one step in a flight of stairs. A *staircase* consists of one or more flights of stairs, and includes landings. A stairwell refers to the compartment through a building in which stairs are placed.

[2] *Biomechanics* refers to the physiological and behavioural aspects involved in producing human motion, and in this case, the requisite body movements for descending down a staircase [1].

those that are behind them and additionally may require assistance from others [12], [13]. Other factors such as reduced lighting and smoke can increase evacuation times as people become more cautious and hesitant in their descent [14]–[16].

Understanding staircase evacuation in buildings also involves a general understanding of human performance during egress. When first confronted with a fire, the commonly reported actions taken by people include: attempting to extinguish the fire, inaction, alerting others, searching for more information or evacuation [17]–[19]. Given the variety of these potential actions, the assumption that people will immediately evacuate might be overly optimistic. In addition, when people do evacuate, they are more likely to take exits that are more familiar to them, which may not be the best routes for evacuating timely and / or safely [20], [21]. This can be further compounded if the location of stairwells and emergency exits are not obvious to evacuees due to missing or damaged signage [22]. Evident cues, encouraged actions and behaviours (e.g., handrail use) during staircase evacuation may improve occupancy flow and reduce the risk of injury during egress.

1.2 General risks of staircase descent

Overall, staircase descent is a precarious activity and is associated with the risk of trips, missteps, and falls [23]. A longitudinal study covering 1990-2012 revealed that approximately 1.07 million people per year in the United States visited the emergency department due to stair-related injuries [24]. Additionally, Canadian statistics determine that in 2010, falls from stairs were the leading cause of fall-related deaths, and were second to falls on level ground in hospitalizations, emergency visits and permanent disability [25].

Biomechanical analyses of movement on stairs during evacuation has the potential of indicating the physiologically challenging aspects of staircase descent and the consequential risks of falling and injury (see Section 3 for more details). Additionally, the determination of how gait patterns (i.e., the manner in which a person walks; also see Table 2) and by extension evacuation speeds evolve over time and in different situations can provide more realistic data for evacuation models, (e.g., moving through confined spaces or reacting to smoke [26], [27]). Biomechanical data for evacuation further shows promise by considering the heterogeneity of movement in different areas (e.g., stair landing, first steps & mid-stair), as well as among different demographic groups [26]. More broadly, such an analysis could point to recommendations for safer staircase design and evacuation procedures.

1.3 The present literature review

The primary goal of this literature review is to review and summarize findings from studies on the biomechanics as they relate to building fire evacuation. The paper begins with an overview of the biomechanics of staircase descent, followed by sections on balance control, processing of visual, proprioceptive, and vestibular information as they relate to the task of staircase descent. We then discuss limb coordination, postural stability, and fatigue. Finally, we consider the relevance of grasping handrails and broader aspects of staircase design itself. In each subsection, general literature on each topic is being reviewed and then linked to evacuation procedures. Where possible, immediate implications for evacuation planners are highlighted. We conclude with a summary discussion of the review, explore its relevance for fire safety engineers, and outline future research needs.

2 Methods

Following recommendations outlined in Khan et al. 2003 [28], the research protocol was structured based on the primary research question of characterizing the biomechanics of staircase descent and its associated factors (Step 1). To identify relevant work (Step 2), our literature search methods comprised keyword searches (e.g., evacuation, stair, staircase, staircase descent, biomechanics, gait, movement speed, etc.) in relevant journals in fire safety engineering and biomechanics (for example, *Fire and Materials* or *Gait & Posture*), database searches in Scopus, Google Scholar, ScienceDirect, and citation chaining/targeted searches through relevant bibliographies. Generally, articles that included the search terms “biomechanics”, “stair descent”, “staircase descent”, “stair evacuation” in the title, abstract, and/or keywords were collected and further assessed.[3] Due to the multifaceted nature of staircase descent, particularly in evacuation scenarios, key aspects relevant to staircase evacuation were identified and constitute the following sections of this review. Within each section, a similar process of keyword and targeted

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[3] Note that we used wildcards (e.g., “stair*”) in our search strategy.

searches were conducted. The sources were accessed through the libraries of the National Research Council Canada and Carleton University. For publications without full text access from either of these two libraries or through interlibrary loan, abstracts were considered, or the source was ignored. The literature identified included but was not limited to reports and journal articles from biomechanics, human factors, and fire safety engineering. Selected articles, within each section and overall, were prioritized based on peer-reviewed empirical studies, summative reviews on relevant subject areas (e.g., photoluminescent markers and staircase navigation) and official technical reports (Step 3; see Table 1 for categorization of articles based on type of source).

Table 1. Research articles included in this review categorized by type of source. Note that references cited for definitions and glossary are not included in this table.

Category	Examples	Number of studies
Peer-reviewed journal articles	Randomized controlled studies, observational studies	113
Technical Report	Building Codes, Policy Documents	13
Working Papers	Conferences papers/proceedings, manuscripts	21
Summative Reviews	Book Chapters, Meta-Analyses	6

Within these criteria, there was a greater preference for articles published in the last ten years (excluding seminal work in the respective subject area). No article older than 1965 was included in this review. Other than that, the search process was not restricted to a certain time period, journal, field, or geographical location. An important criterion was the precision of the description of study protocol, sample, data collection, and analysis methods.

The evidence is summarized (Step 4) in Sections 3 through 7. In each section, the general findings are presented and then their relevance for staircase evacuation discussed (Step 5).

Table 2. Glossary of common biomechanical nomenclature in staircase descent and associated definitions. Paraphrased from Whittle (2007, p. 234-241) [1] and references therein, as well as [29] and [30].

Term	Definition
Cadence	Frequency of gait cycle completion over time.
Centre of Mass (Gravity)	The point in an object where the mass is at its highest concentration.

Centre of Pressure	The physiological response to shifts of centre of mass. In the context of locomotion, the point at which an upward force applied from the ground (ground reaction force) occurs in response to the downward force of the foot.
Foot Clearance (vertical)	Distance between either the floor or a step tread and the bottom of the foot.
Foot Clearance (horizontal)	Distance between an obstacle and the heel and front of the foot respectively.
Foot Placement	Applied forward to the ground. Foot placement can be oriented forward, side or backward.
Gait	Manner/Style of walking.
Gait Cycle	Successive events involved in walking where one foot rests on the ground, leaves the ground and again makes contact on the ground. The gait cycle comprises *stance* and *swing phase*.
Margin of stability	Horizontal distance between the centre of mass of a pedestrian and the heel of the leading foot.
Postural Stability	The ability to maintain an upright position, metrics of postural stability including centre of mass and centre of pressure.
Speed	Rate of movement. In terms of evacuation, speed can be defined as either the total amount of time to evacuate or the rate of movement (distance over time), excluding periods of rest.
Stance Phase	The phase of the gait cycle beginning with one foot on the ground, until it lifts off the ground.
Swing Phase	The phase of the gait beginning with one foot leaving the ground, until it touches the ground.
Weight Acceptance	The phase of the gait in which the joints absorb the impact from moving forward

3 Overview of the biomechanics of staircase descent

Staircase descent is described by the gait cycle (see Table 2 for a glossary of common biomechanical terms describing human staircase descent), which is the sequence of movements enacted during walking [1]. The gait cycle involves two phases: stance and swing. In the stance phase, individuals adjust their weight, either from the previous step or level ground, to lower down to the next step. In the swing phase, the foot pushes off the stair tread and guides the body position as it descends. Figure 1 illustrates these movements during staircase descent. The weight of the trailing foot is shifted to the leading foot in order to continue the cycle. Balance at this moment is unstable, and risk of falling is highest in this phase [31].

Staircase descent has been indicated to have a greater inherent risk of falling compared to staircase ascent and level walking as there is a greater discrepancy with the lowering of the centre of mass (gravity) of an individual and the centre of foot pressure (the weight put on the foot during descent). Additionally, staircase descent involves propelling oneself forward and stopping before falling which involves added risks [32], [33].

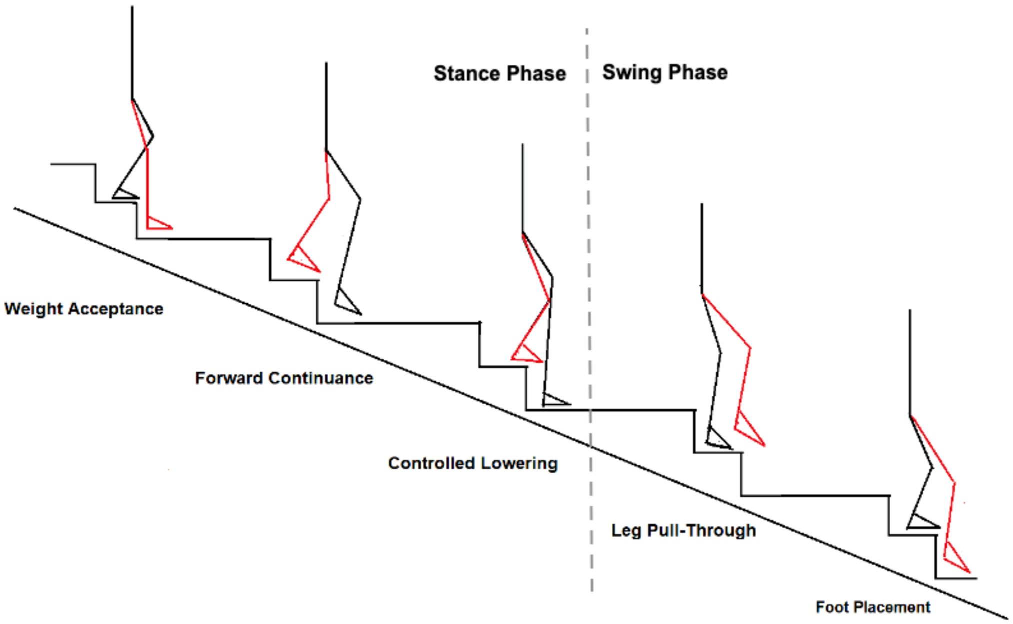

Figure 1. The gait cycle of staircase descent. Adapted from Novak et al. (2010) and Bulea et al. (2014). Red signifies the leading limb.

Staircase descent primarily involves movements in the lower extremities, specifically, in the knee and hip extensors. In addition, the upper body is involved, for instance, through grasping of rails for support and balance (see Sections 4.3 and 6). Staircase descent requires a considerable amount of power absorption in the ankle and knee joints, and requires increased energy demands, in comparison to level walking [32], [36].

3.1 Walking speed

Walking speed during staircase descent can vary considerably (see Table 3, Table 4 and Figure 2). For instance, Protopapadaki et al. (2007) found in a laboratory study that the average walking speed during staircase descent in young adults was approximately 0.56 m/s [37]. Whereas, Peacock, Averill, and Kuligowski (2010) report descent walking speeds observed during fire drills up to 0.83 m/s (in a 6-storey building) [38]. This study also showed that staircase descent speed varies as a function of occupant density and travel distance (see Table 4). Figure 2 and Table 3 show average and median speeds from several studies, weighted by the number of participants reported. A particularly interesting study was reported by Sharifi et al., who tested staircase descent of heterogeneous groups of pedestrians in a semi-controlled setting (i.e., unimpaired pedestrians walking with visually or mobility impaired pedestrians) and found comparable results as [38]. In addition, the authors documented that heterogeneous groups descended on average 0.13 m/s slower than homogeneous groups (i.e., those comprising only able bodied pedestrians).

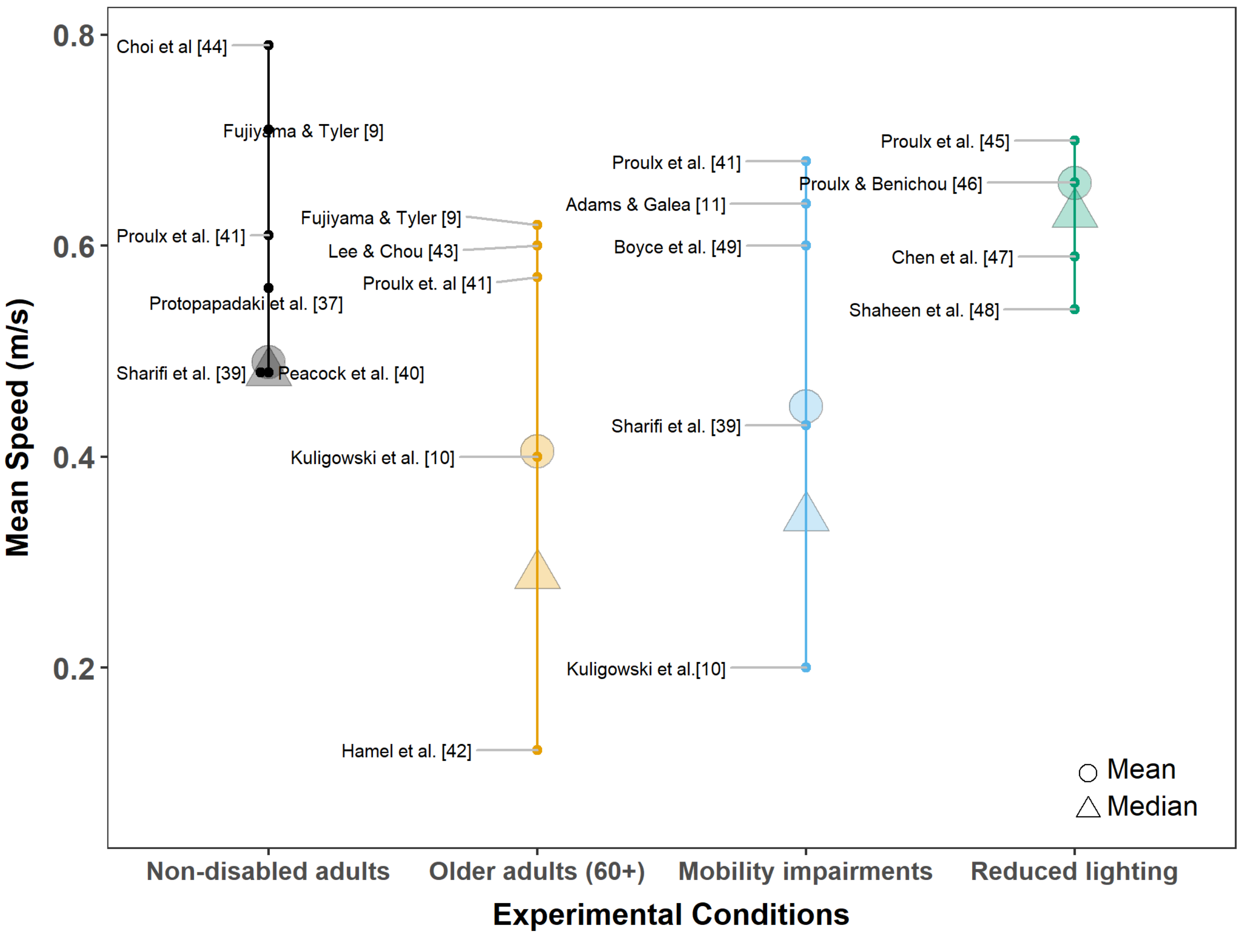

Figure 2. Staircase descent walking speeds in selected studies. All data show unimpeded walking speed. Most data are reported as in their source. Some data points ([9], [11], [41], [44], [56]) are averaged across experimental conditions or studies. Each

bar denotes the mean walking speed across studies within each category (Controls, mobility impairments, older and reduced lighting). Triangles denote medians and circles denote averages, both weighted by reported sample size.

Table 3. Unimpeded staircase descent walking speeds (m/s) in selected studies and conditions (also see Figure 2).

Condition	Mean weighted	Median weighted	Mean unweighted	Median unweighted	Min	Max	Number of studies
Non-disabled adults	0.49	0.48	0.61	0.58	0.48	0.79	6
Older adults (60+)	0.40	0.29	0.46	0.57	0.12	0.62	5
Mobility impairments	0.45	0.34	0.51	0.60	0.20	0.68	5
Reduced lighting	0.66	0.63	0.62	0.62	0.54	0.70	4

Table 4. Selected studies on average descent speeds during staircase evacuation.

Reference	Description and comments	Conditions and groups	Descent speed (m/s) ± SD
Protopapadaki et al. [37]	Laboratory study of staircase descent (four steps)	Younger adults (18-39 years)	0.56 ± 0.06
Sharifi et al. [39]	Groups of participants repeatedly walking (at level of service C and D; middle density) on a laboratory staircase (18 steps)	Non-disabled adults (18-80 years)	0.48 ± 0.19
		Visually impaired adults	0.39 ± 0.16
		Non-motorized mobility impaired adults	0.43 ± 0.20
Peacock et al. [40]	Data observed during fire drills from office buildings; observational study	6 storeys; 273 evacuees	0.78 ± 0.23
		10 storeys; 793 evacuees	0.44 ± 0.19
		11 storeys; 127 evacuees	0.62 ± 0.26
		13 storeys; 226 evacuees	0.69 ± 0.09
		18 storeys; 1148 evacuees	0.44 ± 0.15
		24 storeys; 593 evacuees	0.56 ± 0.12
		31 storeys; 525 evacuees	0.52 ± 0.10
Proulx et al. [41]	Evacuation in three high-rise buildings; observational study *	Older Adults (65+ years)	0.57
Hamel et al. [42]	Laboratory study of staircase descent (seven steps)	Older adults (75+ years)	0.122
Lee and Chou [43]	Laboratory study of descending gait velocity on a staircase (three step)	Younger Adults	0.60 ± 0.10
		Older Adults	0.66 ± 0.09
		Male	0.83

Choi et. al [44]	Staircase descent speeds in a 50-storey building; observational study	Female	0.74
Fujiyama and Tyler [9]	Laboratory study of staircase descent at various walking speeds *	Younger adults (25 – 60 years) – normal walking speed	0.71
		Older adults (60 – 81 years) – normal walking speed	0.62
		Younger adults – fast walking speed	1.01
		Older adults – fast walking speed	0.79
Proulx et al. [45]	Evacuation of high-rise building; observational study	No light + Photoluminescent markers	0.57 ± 0.12
		Full lighting	0.61 ± 0.10
		Reduced lighting	0.70 ± 0.15
		Reduced lighting + Photoluminescent markers	0.72 ± 0.09
Proulx and Bénichou [46]	Evacuation of an office-building; (Second) observational study	Reduced lighting	0.66
		Photoluminescent L shaped marker at the edge	0.66
		Photoluminescent markers 1 inch across each step	0.40
		Photoluminescent markers 2 inch across each step	0.57
Chen et al. [47]	Descent speed of group evacuation of a residential building; observational study	Full lighting	1,15 ± 0.22
		Reduced Lighting	0.59 ± 0.05
		Light transmittance of 27% (simulating light smoke)	0.55 ± 0.08
		Light transmittance of 16% (simulating heavy smoke)	0.50 ± 0.13
Proulx et al. [41]	Evacuation in three high-rise buildings; observational study *	Participants with limited mobility	0.68
Shaheen et al. [48]	Laboratory study of staircase descent in older and visually impaired participants.	50 lux	0.54 ± 0.14
		100 lux	0.56 ± 0.15
		200 lux	0.56 ± 0.15
		300 lux	0.58 ± 0.15
		200 lux distributed	0.57 ± 0.15

Adams and Galea [11]	Vertical measure of mobility assisted stair descent in 14 floor hospital building; observational study [*]	Evac+Chair	0.81
		Carry-Chair	0.57
		Stretcher	0.55
		Drag Mattress	0.62
Kuligowski et al. [10]	Evacuation of older adults (65+ years) with and without mobility impairment; observational study.	Walking with cane	0.25 ± 0.07
		Assisted by other occupants or staff	0.21 ± 0.16
		Assisted by firefighter	0.11 ± 0.04
		Descent device	0.21 ± 0.05
		No assistance	0.29 ± 0.12
Boyce et al. [49]	Laboratory study on staircase descent in non-emergency situations	Mobility impaired	0.33 ± 0.16
		Control group	0.7 ± 0. 26
Galea et al. [50]	Evacuation of high-rise building (World Trade Center); retrospective accounts and evacuation modelling	2001 World Trade Centre – Survivor Accounts	0.33
Peacock et al. [38]	Occupant movement speed; observational study from high-rise building	6 storeys, Non-firefighters	0.83 ± 0.18
		6 storeys, Firefighters	0.73 ± 0.26
		18 storeys, Non-Firefighter	0.40 ± 0.09
		18 storeys, Firefighters	0.54 ± 0.18

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[*] *Values are averaged across staircases.*

3.2 Cadence, foot clearance and foot placement

An analysis of cadence, foot clearance, and foot placement can provide a more in-depth understanding of the underlying mechanisms compared to simply reviewing overall movement. The uncontrolled *cadence* (i.e., the number of step cycles over time) in young adults is described to be within the range of 110 steps/min [51] to 136 step/min [52]. Descent speed and cadence are influenced by height, with shorter individuals exhibiting faster walking speeds and higher cadence [53]. Staircase movement is generally associated with a larger joint range of motion and joint moments than level walking [54], [55].

Distance between a step tread and the bottom of the foot during the swing phase is known as *foot clearance*. Foot clearance is often the highest at the beginning of the descent and then is refined as one descends further down the stairs. If a person’s foot clearance is insufficient for the dimensions of the stairs, this could result in trips or falls [56], [57]. Pedestrians tend to increase their foot clearance in conditions of perceived difficulty (e.g., reduced lighting) or fatigue (see Section 5) as a compensatory strategy to ensure stair clearance [58], [59] (see Table 5 for details).

A related aspect influencing staircase descent is *foot placement*. Foot placement is often measured as the distance from the heel to the base of the stair tread or the overhang distance between the edge of the stair tread and the tip of the foot. Jackson and Cohen [60] found that 55% of staircase accidents in their study were the result of misjudgments in foot placement resulting in trips and falls.

These more in-depths levels of analysis may offer insights for interventions towards safer staircase evacuation procedures. For instance, placement of high contrast photoluminescent markers or slip resistant stair treads may reduce the risk of falls, by improving foot placement or providing wider margins of stability (also see Section 4.1.1, Section 4.3, and Section 7).

Table 5. Selected results on foot clearance under specific visual conditions

Reference	**Description and comments**	**Conditions and groups**	**Average foot clearance (cm ± SD)**
Hamel et al. **[57]**	Laboratory study of staircase descent in ambient or reduced lighting	Young adults (24 ± 3.3 years) - 3 lux	2.30
		Young adults - 300 lux	2.07
		Older adults (73.7 ± 1.9 years) - 3 lux	2.65
		Older adults – 300 lux	2.15
Elliot et al. **[58]**; Experiment 1	Laboratory study of middle step horizontal clearance with or without tread markers	No tread marker	4.1 ± 1.7
		Abutting	3.9 ± 1.6
		1 cm tread edge	3.9 ± 1.4
		3 cm tread edge	3.5 ± 1.7
Kesler et al. [30]	Laboratory study of passing vertical foot clearances of firefighters during descent	Pre-firefighting	18.9
		Post-firefighting	19.8
Gallagher & Callaghan **[59]**	Laboratory study of horizontal passing clearances of descent of an oblique staircase on an angled path; descent angle was manipulated.	0 ° (perpendicular)	13.3 ± 2.7
		25 °	15.8 ± 3.1
		45 °	17.4 ± 3.4

3.3 Age and staircase descent

Age is an important factor influencing staircase descent. In the absence of any health conditions, older adults (ranging from 50-65 and older) generally exhibit lower cadence, shorter step length, increased loading in their hips and ankles, and slower walking speeds [9], [52], [61], [62]. In addition, gaits of older pedestrians are typically less stable, as indicated by increased postural sway and higher margins of stability (findings are inconsistent, however; see Table 6 and Table 7). Walking patterns of older adults are described to be risk averse, analogous to the behaviour exhibited by those of all ages when walking on ice [63], [64] .This can be interpreted as an adaptive strategy, since older adults are at a higher risk of falling and the potential consequences are more severe.

Lockhart et al. [64] measured the slip recovery threshold values for both older and younger adults and found that older adults slipped longer distances (i.e., the distance a foot travels during a slip is larger in older adults compared to younger adults; an indicator of severity of slips) and fell more often. Horizontal heel contact, which is a factor increasing the likelihood of falls, is more common in older adults. These effects can be further compounded by joint pain and reduced range of motion [65].

Older adults are especially apt to alter their descent as a compensation strategy in response to age-related declines in motor ability. Hortobágyi and DeVita [66] found that elderly women compared to younger women were more likely to exhibit stiffness in their lower limbs, specifically less flexibility in their feet (dorsiflexion), knees and ankle movements. They reported 50% greater stiffness in lower extremities. This is attributed to compensatory changes in posture in response to aging. In addition to decreased joint range of motion, aging reduces muscle strength and muscle mass [67]. Thus, elderly individuals were more likely to adopt small joint movements and strategies that reduced the amount of pressure on the joint muscles. This demonstrates how older individuals are also variable in the descent strategies that they employ while walking down staircases. Generally, individuals can adjust their gait as they walk down a staircase in order to reduce the weight that is absorbed by the ankle, knees and hip joints. Interestingly, walking backwards down a staircase has been demonstrated to be an effective descent strategy as it reduces weight placed on the knee extensors and increases foot clearance, when compared to forward descent and level walking [68]. However, this strategy might not be suitable for evacuation conditions. Older individuals and/or those with impairments often place both feet on each step for stability or will walk down the stairs sideways [36]. King et al. [69] found that increased *weight acceptance* – i.e. the phase in the gait cycle in which the joints absorb the impact from moving forward [70]– is required by older adults descending using one step at a time. This was compared to walking down sideways which did not demonstrate an increase in weight acceptance.

4 Balance control during staircase evacuation

Balance control is especially relevant to the biomechanics of staircase descent. Balance control is the maintenance of postural stability in response to environmental and health-related factors. Coordinating balance involves three systems: visual, vestibular and proprioceptive. Visual information in the context of staircase descent refers to the information related to the staircase environment as an individual descends downwards. The vestibular system provides information about location in space and motion detected from the movement of head, primarily through organs in the inner ear [71]. Proprioception refers to a general awareness of the body's position relative to space, especially when the body is in motion [72]. In the absence of any deficits these three aspects are integrated together to create a coherent percept of balance. When one feature is impaired (e.g., vision), the other two are often able to compensate for the deficit due to shared neural connections (recently in [73]). This is pertinent to evacuation in conditions of reduced visibility and evacuating those with impairments (visual or other). Additionally, somatosensation (i.e., sensation received from the skin, limbs and joints) provides tactile/sensory information from the skin and muscles and can also contribute to staircase descent, particularly through handrail use. We begin this section first with a discussion of how visual information influences balance and staircase descent generally and in evacuation conditions, particularly.

4.1 General mechanisms of visual Information processing

Visually guided locomotion is essential to successful staircase negotiation. During staircase descent, a pedestrian's gaze tends to fixate on future step locations (around four steps ahead on average), and to a lesser extent on handrails or other features [74], [75].

Vision is often dichotomized based on functional role: *central* and *peripheral* vision. Central vision is generally used for detailed and focused viewing, such as object recognition. Peripheral vision, by contrast, captures gross contours and is better suited for motion detection [76]. An analogous division of the functional roles of vision for staircase descent is the role of vision in immediate action (i.e., for guiding foot placements down the steps) and for extracting general spatial features from the environment (i.e., the shape and the height of the staircase, the location of a handrail; [77]). Central vision is most useful in immediate action, such as identifying and fixating stair edges while peripheral vision is useful for spatial features, such as the body's position relative to the stairs and general staircase geometry. Peripheral vision is primarily integrated into the vestibular and proprioceptive systems for balance control, although there are some theoretical debates on the relative contributions of central and peripheral vision on postural control (see [78]–[80] for more details).

Focussing on central vision, the most salient visual information captured during staircase descent is *contrast sensitivity*. Contrast sensitivity refers to the ability to distinguish the edge from the rest of a surface based on visual contrast. With respect to staircase descent, contrast sensitivity is the ability to distinguish the stair edge from the next stair tread. This is essential to staircase descent as gaze fixations are often aimed at stair edges [81]. Contrast sensitivity can be reduced due to poor illumination, visibility, or low vision, which can arise from aging, or from acquired visual deficits [57]. In one study, loss of contrast sensitivity as a result of reduced vision yielded increased caution and slower step clearance while descending down a staircase. Specifically, there was more instability in the medio-lateral centre of pressure (balance) when participants descended down the stairs with blurred vision [82].

Low contrast and reduced contrast sensitivity can be mitigated by adding tread highlighters which increase the contrast between the stair edge and the tread (an example is shown in Figure 3). Indeed, tread highlighters have been demonstrated to facilitate safe staircase descent, particularly in those with low vision and under low visibility conditions [46]. Specifically, Elliott et al. [58] found that tread highlighters help to guide foot placement as one descends on the stairs (recall that foot placement is associated with increased risk of falling, see Section 3). Since foot clearance is typically increased when exercising caution and increased foot clearance (up to a certain point) aids in descent (see Section 3), Elliott et al. [54] determined that using a tread marker that was flush with the stair edge increased the heel clearance more than a tread marker set 3cm back from the edge or not using a tread marker at all.

4.1.1 Vision and descending staircase evacuation

In the context of staircase evacuation, a number of sub-optimal visibility conditions need to be considered. If electric power is lost, staircases may only be illuminated by emergency lighting, which is less bright compared to “normal” ambient light. Smoke can further reduce visibility through obscuration and eye irritation. As reported in, Yamada and Akizuki [83], Jin found that the extinction coefficient (a measure of smoke density and visibility) of 1.15 is comparable to walking in total darkness [14]. Additionally, irritant smoke on its own can physiologically impair vision [84]. More general studies on the effects of smoke in evacuation demonstrate slower walking speeds and greater reliance on other sensory information, such as tactile information from handrails or the walls ([14], [85], [86]; see [87] for a comprehensive review).

Biomechanical analyses of walking in reduced lighting on staircase descent found that reduced lighting encourages compensatory adjustments to foot clearance and more cautious landing as measured by vertical peak force, particularly in young adults [23], [57]. Boyaniniska [88] determined that lower lighting conditions yielded reduced stability while walking down stairs. A promising solution for this is the use of photoluminescent markers to improve the contrast in reduced lighting by illuminating in the dark. Notably, photoluminescent markers have been cited as being more visible in cases of extreme smoke conditions than other emergency lighting systems (e.g., incandescent, fluorescent). While there is little direct information on the biomechanical effects of photoluminescent markers on staircase evacuation, photoluminescent markers have been indicated to be a useful method of way guidance in evacuation procedures down staircases and in hallways [45], [46]. Certainly, the research findings suggest that photoluminescent markers are an effective strategy to reduce the risk of falling during staircase evacuation. As illustrated by Figure 3, photoluminescent markers that are placed near to the edge of the stair tread can be used to improve contrast sensitivity between steps. This could also mitigate the effects of reduced or blurred vision during evacuation.

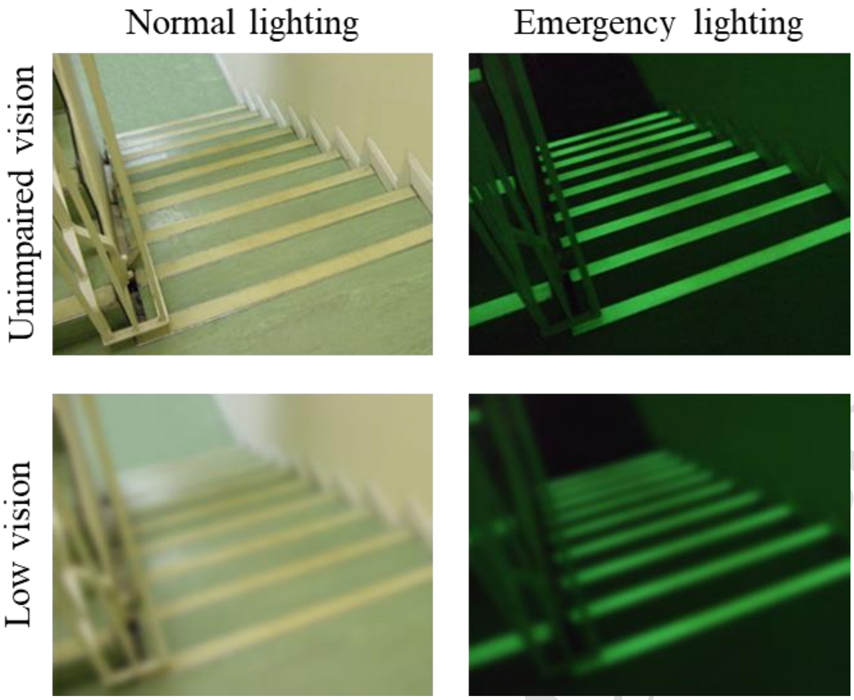

Figure 3. Illustration of visibility under normal and emergency lighting conditions on a staircase for unimpaired and simulated reduced vision; Photoluminescent markers are shown in all images. In the bottom row, images are artificially blurred to simulate visual acuity at roughly 20/200 (threshold for legal blindness in Canada and the United States);

4.2 Proprioceptive and vestibular information

During staircase descent and for general mechanisms of balance, vision is typically the dominant sensory modality[4] [77], [89]. That said, both the proprioceptive and the vestibular systems contribute to overall balance and upright posture. Their relative contributions are particularly evident in instances of balance recovery from trips and missteps. Muscle activation, as a measure of proprioceptive input, can cause deviations to walking patterns and centre of mass. For example, muscles activated in the neck and left side of the body can cause deviations to the walking trajectory of the right side of the body and symmetrical muscle activation in the neck is associated with an increase in walking speed [62], [90], [91]. Indeed, proprioception is a factor influencing staircase descent (and ascent) times, particularly in older individuals [92]. Inappropriate proprioceptive input can lead to inappropriate muscle activation and increase the risk of falling during staircase descent. Startzell et al. [33] indicated that proprioception is

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[4] A simple illustrative example for this, is the increased difficulty of standing on one leg while a person's eyes are closed.

pertinent for the awareness of limb position on the stairs, particularly during the initiation phase (i.e., the first descending step) and further down as people familiarize themselves with the staircase design. Once this proprioceptive awareness about step configuration is established, there is less reliance on visual information, as measured by differences in gait speed and head angles in visual conditions [93], [94]. This indicates that proprioception can compensate to a degree for visual deficits and low visibility conditions.

The vestibular system contributes to balance through the vestibulospinal reflex[5]. This reflex monitors disturbances to posture and activates antigravity (extensor) muscles, in the neck and trunk respectively, to stabilize the body position [62], [96]. The contribution of the vestibular system to balance is correlated with the amount of stability the individual currently experiences [97]. The influence of vestibular input is phase-dependent, such that, manipulating the vestibular input to muscles in the lower leg has differential effects depending on the phase cycle [98]. Using electrical stimulation to influence the firing of the vestibular nerves, Kern (2018) determined that coherence (the covariation between vestibular input and muscle activation) occurs during the stance phase during level walking (and staircase ascent) compared to the swing phase in during staircase descent. The author concludes that this is attributable to the greater need of balance control during descent as the body is being lowered.

4.2.1 Proprioception and vestibular information as a compensatory strategy

In the absence of visual input (i.e., in total darkness), proprioceptive and vestibular information can be used in staircase evacuation. Nashner and Berthoz [100] describe this compensatory capacity, as “sensory re-weighting” where the relative contribution of each sensory system to balance control depends on the environmental conditions and the availability of relevant information to each system. While there are no direct studies related to staircase evacuation, sensory re-weighting generally has been demonstrated to reduce the postural sway during balance loss and recovery [101]–[104]. A study measuring the influence on sensory conflict during staircase descent determined that the absence of vision caused individuals to adjust their pre-contact muscle activity and accommodate softer foot placements during descent.

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[5] Also known as postural reflex, this reflex maintains the posture and balance of the body [95].

In comparison, when visual information was perturbed during descent, there was less time to adjust for the abrupt sensory conflict, leading to harder landings [89]. This may extrapolate to when there are sudden changes to visual information during staircase evacuation.

4.3 Limb coordination and postural stability

Two key measures of postural stability are *postural sway* (horizontal movement of the body around the center of gravity) and the *margin of stability* (horizontal distance between the centre of mass of a pedestrian and the heel of the leading foot [105]; see Table 6 and Table 7). Balance maintenance and recovery also involve the use of upper and lower limbs to adjust the base of support in response to destabilization due to gravity and other external forces. Upright posture is maintained through the centre of mass and base of support being aligned [106].

In a broader sense, increased *postural sway* has been suggested to reduce occupancy flow and evacuation rates, and has been considered in staircase width recommendations [107]. Sway amplitudes are correlated to movement speed and negatively correlated to pedestrian density ([108] see Table 6). For engineering calculations, postural sway translates into lateral oscillations of agents in an evacuation simulation (also see Section 8). Generally speaking, postural sway increases with available space, as people have more room to stabilize their posture and decreases with pedestrian density.

Focussing on the lower limbs, strategies involving the coordination of the limbs are classified as either fixed-support strategies (where the legs and feet stay firm in place to maintain balance) or change-in-support strategies, which is tantamount to compensatory stepping [106], [109].

Fixed-support strategies are best characterized by a stiffening of limbs and joints to control the movement of the body’s centre of mass. Two commonly known fixed-support strategies are the ankle and hip strategies. Horak and Nashner [110] describe the “ankle strategy” as stiffening of the muscles of the ankles which extends in succession further out to the legs and trunk of the body. The “hip strategy” involves the hips and trunk muscles stiffening simultaneously. The authors note that the hip strategy involves very little stiffening in the ankles and the cascade of muscle activation in the ankle strategy reduces the amount of stiffening in the hips. Additionally, in their work, Horak and Nashner [110] determined that pedestrians will adopt these strategies as a function of prior experience (e.g., having successfully used the ankle strategy in the past) and the length of the support surface.

Compensatory stepping (i.e., making a step to regain balance) as a change-in-support strategy involves accommodating shifts in posture and weight acceptance. Such balance recovery strategies are preferable to the fixed-support strategies, as stepping can provide a new base of support rather than reinforcing the current one in place [105], [106]. Additionally, fixed-support strategies can only be used for smaller perturbations to upright posture, while compensatory stepping (and reaching) can be effective strategies for both larger and smaller disturbances to balance. Maki and McIlroy [106] determined that change-in-support strategies are preferentially chosen by participants when given the choice. The authors also found that compensatory stepping does not require the gait initiation and other anticipatory control actions needed to enact fixed-support strategies. Indeed, when unexpected perturbations occurred to participants during staircase descent, Gosine et al. [111] found that all participants made compensatory steps to control the movement of their centre of mass. Compensatory stepping is an important aspect for preventing falls during staircase descent. Van Dieën et al. [112] determined that unexpected shifts in ground height did not allow individuals the time to reactively increase or decrease their step length. At greater heights individuals generally switched from landing on their heels to landing on their toes, which also increased the change of knees buckling under weight absorption.

A remaining question is how this may be affected by other factors in evacuation scenarios. For example, it is unclear whether current stair heights are suitable for accommodating potential loss of balance during evacuation. Further research will also have to address, if compensatory stepping as opposed to fixed support strategies, are more or less effective and risky in low visibility conditions that may occur during evacuation. For instance, occupants may be hesitant to engage in compensatory stepping, when the next step is hard to see.

4.4 Summary

- Balance and postural control are integral to successful staircase negotiation and evacuation. Balance comprises three sources of sensory information: visual, vestibular and proprioceptive.
- Visually guided staircase descent involves central and peripheral vision, which are respectively used for immediate action and extracting features from the environment.
- Vision during descent is most impacted by the abundance of contrast sensitivity between the edges of one step to the other. Low contrast sensitivity can be mitigated by tread highlighters and by photoluminescent markers, which can provide increased visibility in low lighting conditions.
- Proprioceptive and vestibular input are essential to balance recovery, initiating movement and compensation for visual deficits.
- Postural sway and margins of stability are integral to both the maintenance of individual balance and occupancy flow through pedestrian density.
- The overall coordination of limbs is maintained through fixed-support and change-in-support strategies, with the latter being preferred in cases of postural instability.
- Further research should investigate proprioceptive, vestibular information and postural balance as compensatory strategies in the absence or reduction of visual information. Additional research is needed to investigate balance and postural control in the contexts of staircase evacuation.

Table 6. Selected results on postural sway (measured in cm/s) as measured by centre of mass

Reference	**Description and comments**	**Conditions and groups**	**Speed of postural sway (cm/s) ± SD**
Wang and Gillette **[113]**	Laboratory study of medio-lateral centre of pressure velocity while carrying loads	No load 20% body mass bilateral load 20% body mass asymmetrical load	7.96 ± 2.28 8.57 ± 2.62 9.54 ± 3.30
Mian et al. **[114]**	Laboratory study of medio-lateral centre of mass velocity with respect to age	Younger men (28 ± 4 years) Older men (76 ± 3 years)	14.4 ± 2.7 15.1 ± 3.1
Reid et al. **[115]**	Laboratory study of medio-lateral centre of pressure velocity during descent, comparing age and handrail use.	Younger adults, no handrail Older adults, no handrail Younger adults, handrail Older adults, handrail	17.9 ± 6.9 17.4 ± 4.3 16.9 ± 6.6 16.9 ± 5.4

Table 7 Selected results on the margin of postural stability

Reference	**Description and comments**	**Conditions and groups**		**Margin of stability (cm) ± SD**
Bosse et al. **[116]**	Laboratory study of margins of stability, influence of age.	Initiation of double support phase	Older adults	-4.1 ± 5.6
			Younger adults	-0.6 ± 4.4
		Initiation of single support phase	Older adults	-18.0 ± 5.2
			younger adults	-13.6 ± 4.9
Qu **[117]**	Laboratory study of margins of stability, lower limb muscle fatigue during descent	Anterior-posterior margin of stability, Non-dominant foot contact	No fatigue	7.18 ± 3.39
			Fatigue	3.24 ± 2.74
		Medial-lateral margins of stability, Non-dominant foot contact	No fatigue	3.16 ± 1.8
			Fatigue	3.52 ± 1.4

5 Effects of fatigue and smoke

Depending on the evacuation circumstances (e.g., from a high floor of a building, presence of smoke, carrying or assisting other people), individuals evacuating may become fatigued as they move down the staircases. An investigation on the World Trade Centre found that some evacuees reported to have stopped to rest while evacuating, particularly on the landings [50]. The ability to sustain the level of physical activity required for staircase evacuation is contingent on factors such as physical fitness, muscular ability and oxygen uptake. Fatigue can also be influenced by psychological factors such as risk perception and motivation [86], [118]. As a result of fatigue, evacuation speeds can become diminished over time, particularly as resources are reduced. For example, in a study examining evacuation of a high rise building, fatigue was self-reported to occur after vertical distances ranging from 28m to 32m (7th and 8th floor in the particular building; [119]). In addition to reducing movement speed on stairs, fatigue might also increase risk of falling on stairs. For instance, reduced muscle strength as a result of muscle fatigue has been indicated to have influence stair gait [120]. Qu [117] found that lower limb fatigue influenced staircase descent, but interestingly not staircase ascent. Specifically, when fatigued, participants exhibited smaller amounts of flexion (reduction in the joint angle) in the knees, ankles and hips. Recalling that staircase movement is generally associated with a larger necessary range of motion, Qu [117] indicated that fatigue can ultimately reduce postural control, through a reduced capacity for energy absorption (see Section 4). Thus, it can be concluded that fatigue can correspond to increased risks of falling as one descends down the stairs.

More generally, Proffitt [121] argues that the perceived steepness of a slope is related to resource availability, where slopes appear to be steeper under conditions of fatigue, increased physical exertion and poorer physical performance. Such conditions are likely to be present during staircase evacuation and, under this view, could reasonably influence the perception of stairs and one’s gait by extension.

In firefighters, whole body fatigue has been shown to result in greater foot clearances during descent and reduced the foot clearances during *staircase ascent*, which increases the chances of falling by overstepping and tripping, respectively [30]. However, note that these findings are somewhat contradictory to [117]. In addition, Bergmann et al. [122] found no difference in the participants' range of motion in the lower joints after they experienced fatigue. Therefore, a comprehensive understanding of fatigue and staircase movement, particularly in an evacuation context, requires more investigations in various conditions of fatigue and parameters of muscle activity [123].

Smoke can also exacerbate the fatigue experienced during evacuations. Technological systems have been developed to mitigate the risks of smoke exposure on stairs. For example, stairwell pressurization systems have been designed to suppress the migration of smoke onto the stairways; however, a fundamental assumption of these systems is that only a few interior doors remain open during evacuation [124]. Therefore, if larger numbers of occupants evacuate from multiple floors, smoke might travel into a stairwell. The presence of smoke becomes increasingly more likely the longer it takes evacuees to begin their movement, which in turn increases the time required to evacuate due to reduced visibility conditions, detours and smoke inhalation [125].

Muscle activity requires uptake of oxygen from the environment. An increased demand of oxygen with sustained muscle activity puts an increased demand on the cardiovascular system. Carbon dioxide and other substances present in smoke reduce the available concentration of oxygen in the muscle tissue (carbon dioxide has a stronger affinity for hemoglobin than oxygen), effectively reducing the ability of muscles to do work. Fatigue and a reduction in exercise tolerance due to a lack of oxygen begins to occur at blood carbaminohemoglobin (CO_2Hb) concentrations of 5-9%. At higher concentrations, people start to experience headaches and loss of consciousness [4].

While there are no direct studies on smoke inhalation or reduced oxygen on descending staircase evacuation, work on ascending staircase evacuation demonstrates that muscle fatigue reduced the oxygen uptake, thereby reducing the evacuating speeds. Accordingly, less muscle activity allowed participants to maintain an adequate capacity for staircase ascent and ultimately resulted in faster evacuation speeds [126]. Thus, in a general sense, evacuation speeds should be optimized for the fastest speeds that can be sustained for the longest period of movement, while accounting for factors such as fatigue and oxygen availability. Future research is needed, to identify such optimal movement speeds on stairs (and elsewhere).

5.1 Summary

- Fatigue and smoke can reduce one's ability to safely exit in evacuation scenarios. Evacuation speeds are diminished by both the presence of fatigue and smoke.
- Fatigue in particular is influenced by muscular ability and oxygen availability, as well as by psychological factors.
- Smoke reduces visibility and oxygen availability for muscle consumption. This can be exacerbated by smoke travelling upwards through stairwells.
- Considering the cumulative effects of fatigue and smoke over time in evacuation scenarios provides potential research avenues for modelling and optimizing speeds during egress.

6 Grasping capabilities and handrail design

The upper body is also involved during staircase descent, particularly through the use of the handrail or touching nearby surfaces for stability and postural balance. Handrails have three primary uses: preventing falls and maintaining balance, tactile guidance for the visually impaired or in reduced visibility (e.g., due to smoke) and to assist those with mobility issues and those experiencing fatigue [33], [36]. Handrail support from the upper body reduces the demands placed on the lower limbs during staircase movement [33]. The tactile sensory information provided by handrails can be supplemented visually in lower lighting conditions through photoluminescent markers that are placed on the handrails [127].

Handrail use also functions as a psychological support, by increasing the perceived stability of staircase movement, especially in those with a fear of falling or those who have previously fallen [33].

Handrails are an effective way of preventing and reducing the impact of falling during staircase movement [128]. Physically, handrail use has been categorized based on the level of support required for staircase movement. This covers an activity range from no handrail use, (with the exception of use for balance recovery) to continued handrail support with hands gripped around the railing [36], [129]. In terms of balance maintenance and recovery, handrails can significantly reduce the risks of falling and injuries by providing the support to stabilize the centre of mass [128], [130] (e.g., when compensatory stepping is not possible; see Section 4.3).

For staircase descent specifically, the grasping actions for the handrail consist of a pushing motion where force is exerted away from the shoulder to stabilize posture [128]. The grasping capabilities of the handrail depend on the individual pedestrian as well as the design of the handrail. For the physiological affordances of an individual, hand size, wrist, weight (with respect to centre of mass) and arm position are pertinent factors in successful handrail grasping. Circumstantial factors in graspability include the distance away from the handrail, where failure to grasp a handrail is likely to yield more disastrous outcomes for loss of balance [74], [131]. For crowd evacuation, Pauls recommends handrail widths 1,550 mm apart to allow for optimal distance and crowd density. Additionally, this would enable most occupants to be within grasping distance of a handrail at all times [132]. That said, individuals have been demonstrated to be quite adept in grasping the handrail even from larger lateral distances [132]. The combination of such factors is evident through the location of hand placement on the handrail, which optimizes comfort, particularly at the angles at which the relevant joints (wrist, shoulders and elbows) are placed [132].

Affordances of the handrail itself include the shape, size, and height of the handrail. Komisar et al. [133] demonstrated that increased handrail height is associated with decreased forces and decreased muscle exertion for handrail use. The surface area of the rail must be adequate such that it allows for maximally effective contact from a user’s hand. From their studies, Dusenberry et al. [131] recommended handrail dimensions between 32 mm and 70 mm wide to optimize graspability. Circular/oval shaped railings are generally recommended to facilitate grasping [134], [135], although Dusenberry et al. [131] indicated that rectangular and otherwise unrounded handrails can also be used successfully, with the provision that they are designed within certain dimensions. Such dimensions, prescribed within a range of handrail heights have been implemented into building codes [2], [136].

Individuals are attuned to the efficacy of handrails to prevent balance perturbations in conditions of perceived risk. Zeng et al. [137] found that the use of handrails increased in low lighting conditions during evacuation. As previously mentioned, this can be further encouraged through applying photoluminescent markers on the handrails to make them more salient to an individual. In addition, handrails can improve evacuation speeds, particularly when passing a mid-landing, where individuals have to alter their movement trajectories [137]. Additionally, even light handrail use demonstrably improves postural stability in older adults during staircase descent [138]. That said, when staircase descent is not thought to be dangerous, pedestrians are less likely to use the handrail. To further encourage handrail use, handrails ought to be ergonomically and visual appealing to invite usage (i.e., clean and visibly in good conditions) [139]. Encouraged handrail use, through proximity and accessibility of the handrail, during evacuations may be an effective way to reduce the risks of falling and could have beneficial effects on the flow of movement during staircase evacuation. To this point, Pauls [107] notes that military marching formations enables a high rate of occupant flow with a small amount of spacing between individual people.

6.1 Summary

- Handrails aid in balance maintenance by providing support from the upper body. Handrails additionally provide a psychological support as a perceived increase in stability. Perceived risk also influences one’s likelihood to use a handrail. Handrails additionally provide a psychological support as a perceived increase in stability. Perceived risk also influences one’s likelihood to use a handrail.
- The distance from the handrail and its general size and shape influence its graspability.
- During group evacuations, handrails can potentially increase movement uniformity and by consequence occupancy flow rates.

7 Staircase design for evacuation

The staircase geometry and design itself can impact staircase descent and evacuation. As individuals use a staircase, they develop a coherent representation of the staircase geometry in question. Therefore, if the geometry of the staircase were to suddenly change – either as a result of staircase design, damage or an obstruction, this could lead to fall and injury [74]. Supporting this, it has been reported that stairs with inconsistencies in their heights have resulted in greater incidences of falling compared to stairs that were consistent [140].

Building codes have implemented usability requirements and regulations for stairs, such that, the treads ought to conform to certain dimensions of length/width and the risers need to conform to certain heights [2], [136]. The widely adopted 1,100 mm (44 in) stair width resulted from a report on methods to calculate an appropriate minimum stair width. Such methods were derived based on considerations of staircase capacity, flow, phased evacuations and combinations of these respective factors [141], [142]. However, this report has since been criticized for a lack of consideration of postural sway as individuals descend down the stairs, which arguably necessitates a wider stair tread [107], [143]. Additionally, the size of the average person has increased since this provision was given, which would require greater widths to accommodate counterflow (i.e., occupants traveling in opposite directions within the same space) [107]. Accordingly, Templer, Mullet and Archea [144] recommend a minimum tread width of 1,420 mm (56 in).

Generally, staircase design provisions are made with the consideration of the aspects of staircase design (tread length, riser height and nosing) that contribute to the risk of falling and injury [145]. Yet, not all staircases adhere to these recommendations. In a review of staircase design from 2000 to 2012, Kim and Steinfeld found that 61% of staircases featured had at least one occupational hazard in their design. The authors found the most common hazards being missing or inadequate handrails, staircase flights of excessive length and a lack of contrast between the tread edge [146].

Improved staircase design can effectively mitigate the risk of falling [147]. For example, Wright or Roys [148] conducted a survey on injuries sustained from staircase descent and observed that shorter stair treads were associated with a higher risk of falling, largely due to foot overhang. Novak et al. [149] ran an empirical study that manipulated tread lengths and found that the margin of stability was the largest at the longest tread length, which translates into the lowest risk of falling.

Tread width is considered with respect to the occupancy of the building, as movement speed on stairs is tied to pedestrian density (which is a function of the number of pedestrians per available space [150]. From the 2018 version of the International Building Code, stair width is stipulated based on the capacity (occupant load) of a given storey multiplied by the capacity factor of 7.6 mm (0.3 in) per occupant, barring any exceptions [2].

The number of stairways required to be present in a building is similarly subject to occupancy rates. Additionally, the use of stair nosings can mitigate the risk of falling. Walking on stairs with a nosing compared to without a nosing led to a reduced foot overhang during staircase descent [151]. An increase in the step (riser) height increases the power exerted by the lower limbs, such that, more work being required by the muscle-tendon complex [152]. Additionally, increased riser height (12.7, 17.8, 20.3 cm / 5, 7, 8 in) is associated with more forwarded body tilt, particularly in older adults [149].

The intersection of the biomechanics of descent and staircase design are also relevant for describing crowd behaviour during an evacuation. Pauls et al. [107] note that lateral sway and clearance of individuals with respect to the design of the staircase can collectively impact group evacuation times and speeds. Specifically, a greater variability in how individuals move (based on certain factors such as age, walking speed and ability) as they descend down the staircase can cause delays, which by consequence can be influenced based on the width of the stair treads.

7.1 Staircase material

Staircase material is another factor that influences the movement of staircase descent. In an observational study, Kim and Steinfeld [153] determined that glass treads were over eight times more likely to cause falls compared to opaque treads. When using glass treads, participants had slower walking patterns and were more prone to looking at their feet for stability. In an empirical study, participants exhibited slower cadence and anterior-posterior centre of mass and velocity while descending down the glass stairs, compared to the open and closed wooden risers [88]. Overall, there were no significant differences in gait in the open and closed riser conditions, although there were some interactions due to age [88]. The author suggests that the lack of difference between open and closed risers are due to a lack of perceived danger in the experimental set-up. Pauls et al. [107] also indicate that gait demands vary between stairs of different building types, specifically highlighting the difference between the staircases in a tall building, where there are more landings and consequently requires more shifts in gait from staircase to level walking.

7.2 Summary

- Individuals develop a mental model of the design of a staircase as they traverse it. Thus, consistent staircase geometry is important for safe negotiation and evacuation. These considerations are reflected in building codes regulations for staircases.
- Contributory aspects to increased risks of falling and injury include tread length, riser height and the presence of nosing. Tread width coupled with considerations of factors like individual postural sway, walking ability and age can influence occupancy flow rates during evacuation.
- Opaque staircase materials are generally found to be safer for staircase descent compared to transparent ones. Gait demands on staircases additionally vary with the design of the building.

8 Considerations for engineering calculations and evacuation modeling

The findings presented here have potential implications for engineering calculations and evacuation modelling. From a practical standpoint, biomechanical analysis is particularly useful, where it can identify factors that influence collective movement speeds and consequently egress times, as well as factors that increase the risk of falls and injuries. For instance, postural sway influences the amount of space a simulated agent might use [108]. As Ronchi et al. [86] point out, many evacuation models (potentially falsely) assume that fatigue and other such biomechanical factors are fixed or decline linearly over time. Therefore, to address the criticism made by Gwynne and Kuligowski [154] and others that modelling human behaviour in evacuations is unrealistic, greater attention is required regarding the variability that occurs in movement.

Ronchi [155] articulates that modelling approaches tend to rely on empirical data, either to generate the model (data-driven modelling approaches) or to validate it (theory-driven modelling approaches). As movement speed and flow are dependent on factors such as cadence and postural sway, biomechanical analyses provide more realistic information on one's ability to evacuate. To this point, Thompson et al. [156] relate biomechanical data, specifically, height, foot length, and step length to inter-personal distance in order to derive a model for single file pedestrian evacuation across various age demographics. Biomechanical data is also beneficial in modelling the influence of crowd density, as shifts in movement behaviour are the result of the biomechanical characteristics of individuals (e.g., stride length and gait), particularly in how they respond to changes in the environment and crowd flow [157]. Generally, representing movement in biomechanical analyses can provide realistic behavioural information to evacuation models, which at this stage, are often limited to pathfinding and movement in specific trajectories [158].

9 Discussion

Evacuation from buildings via stairs is a complex process that involves various factors both internal and external to the evacuee. This review aimed to highlight the various aspects that influence the biomechanics of staircase descent and possible challenges presented by circumstances of evacuation. The largest threats to staircase descent are balance loss which can occur as a result of visual, vestibular, proprioceptive deficits, physiological factors such as age and fatigue, factors due to the environment as well as elements of the staircase design itself. While the biomechanical factors described in this review are examined in isolation to each other, it is quite evident that they interact and can have cumulative effects on the ability and performance of staircase evacuation. Risks that are inherent to the use of staircases can become increased under evacuation scenarios, where physiological and environmental affordances (e.g., fatigue, smoke and lighting conditions) are suboptimal.

9.1 Limitations

There are some limitations to this review that need to be considered. For instance, successful staircase navigation is determined by multiple variables that likely interact with each other. That is, the conclusions may oversimplify how various factors increase or decrease, for example the risk of falling during staircase descent, and may neglect potential interaction effects between the factors. More holistic research efforts in the future are clearly needed to identify the most relevant biomechanical factors and their effects on staircase evacuation.

In addition, while we follow the approach of a systematic review and have also weighted the available studies (see Figure 2), this work does not constitute a meta-analysis or similar approach. That is, the conclusions that can be drawn are primarily qualitative in nature.

Finally, the current literature review depended on the accessibility of sources. This review is limited to the libraries of the National Research Council Canada and Carleton University. For literature without full text access from either of these two libraries or through interlibrary loan, abstracts were considered, or the source was ignored.

9.2 Future research needs

This review identified several areas that require future research. For example, much of the empirical work summarized here stems from controlled laboratory experiments. Other studies report observations from drills or building evacuations (e.g., see Table 4 for a breakdown on movement speed).While quantitative data from controlled experiments generally provides a high level of empirical evidence [159] it is important to understand that these studies usually focus on individual effects. That is, interaction and comparison of effects are only possible to a limited extent. Conversely, observations from drills provide insights from realistic conditions, however, it is unclear whether findings from one specific observation can be translated to other use cases. It is also challenging to identify cause and effect. For instance, in the data on descent speed reported by Peacock et al. [40] it is difficult to assess if and how the number of storeys and number of evacuees determine average movement speeds. Future research is clearly needed to explore the link between controlled lab experiments and data observed from real world scenarios.

Moreover, the overwhelming majority of biomechanics research views the human physiology and kinematics involved in the movement of individual participants. As evacuation rarely occurs in isolation, biomechanics research in this area should consider parameters that are related to crowd movement and flow and the influence on individual gait patterns. Future studies should consider the influences of evacuation behaviours (running, reactions to hazards, obstacle avoidance, assisting others, crowding/congestion) on the biomechanics of staircase movement and evacuation more generally. For instance, an improved understanding between the speed of movement and the risk of falling during staircase descent could inform instructions for evacuees. Is it safe to recommend making haste during descent, or would an increased potential for falls preclude such recommendations? Such information, could eventually provide guidance for evacuation procedures that currently typically provide relatively vague recommendations for "orderly" and "timely" egress (see [160] for a review).

In addition, an understanding of how movements during evacuation scenarios differs from general staircase descent is paramount to implementing both safer staircase design and evacuation procedures. Cost effective solutions such as photoluminescent markers, handrail design that are well suited for gripping, staircase widths for effective crowd flow and tread highlighters are some of the promising efforts to improve staircase descent. In general, the biomechanical analysis of gait during staircase evacuation presents a promising opportunity to contribute to safer evacuation procedures and staircase design, as well as more realistic modelling scenarios.

9.3 Conclusions

In this paper, we reviewed several biomechanical factors related to descending staircase evacuation of buildings, with a particular focus on parameters known for influencing staircase evacuation (e.g., impaired vision, fatigue, staircase design). Tied to this review, we discussed implications of biomechanical analyses that are relevant to researchers and practitioners in the fields of human behavior in fire, evacuation modelling, evacuation planning and building design.

Given the reliance of current procedures on staircase evacuation, it is critical to better understand its effectiveness and identify potential risks to evacuees. Biomechanical analysis can provide valuable insights that can help to (1) identify risks during staircase evacuation, (2) develop safer designs and procedures for staircase evacuation, and (3) refine computational evacuation models.

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