



Review

A review of stairway falls and stair negotiation: Lessons learned and future needs to reduce injury



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ABSTRACT

Stairways are a common location for falls, and they result in a disproportionate risk of death or severe injury. Stairway falls are a significant problem across the lifespan and are often coincident with risky behaviors during stair use. The mechanics of successful stair negotiation for healthy young and older adults have been well described. These studies imply that current stair design does not offer an optimal universal design to meet the needs of older adults or people with health conditions. In addition, impaired stair negotiation associates with more than impaired strength, including functional impairments of cognitive load, sensory function and central motor coordination. Identification of behavioral strategies or stairway environments that assist or hinder recovery from a loss of balance on stairs remains incomplete. Therefore, future studies should investigate the mechanisms of balance recovery on stairs as well as the effectiveness of environmental interventions to mitigate stairway falls and injuries. Potential areas for evaluation may include modifying stair dimensions, surfaces, handrails, visual cues, and removing distractors of attention. Studies should also evaluate combinatorial interventions on person-related factors, such as behavioral interventions to decrease risky behaviors during stair use as well as interventions on cognitive, sensory, and motor functions relevant to stair use. Moreover, future studies should take advantage of new technologies to record stair use outside the laboratory in order to identify people or locations at risk for stairway falls. Such studies would inform the potential for broad-spectrum programs that decrease the risk of stairway falls and injuries.

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1. Introduction and objectives

Stairway falls are common and often associated with severe injury. Research has primarily comprised epidemiologic studies on the circumstances and consequences of stairway falls as well as kinesiological studies on successful stair negotiation. Many studies of both epidemiologic and kinesiological methods have been recently published on stairway falls and stair negotiation such that the timing is ripe to synthesize lessons learned from this literature and determine future needs. Therefore, this review will (a) describe the relevance of stairway falls as a health concern, (b) review studies on the kinesiology of stair negotiation in young adults, older adults, and individuals with health conditions, and (c) provide suggestions for applying the lessons learned from this past literature as well as suggestions for future research in order to mitigate the risks and consequences of stairway falls.

2. Stairway falls are prevalent and injurious

Falls represent a serious and costly global health concern [1,2], and factors coincident with falls often span conditions associated with the person, the environment, and the task, thereby suggesting that a fall occurs due to interactions among these factors [3–6]. Stair use represents one factor associated with fall risk that relates to both the task and the environment, and this section highlights the specific health concern of stairway falls. Stairway falls represent a leading cause of accidental death among older adults [7]. Use of stairs or steps was reported to be the coincident activity for 7–36% of falls, with most studies reporting the percentages in the high teens or low twenties [3,8–14]. Interestingly, stairway falls appear particularly evident for the middle-aged adult [11–13].

The circumstances of stairway falls often include engagement in risky behaviors, such as using stairs laden with objects, carrying items on stairs, using stairs in stocking feet, and not using a handrail; video analysis suggests 41% of stair accidents coincide with distracted attention, lateral movement, change in handrail use, or reaction to others [7]. Ninety-one percent of young adults and 57% of older adults self-report that they engage in at least some

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of these risky behaviors [7]. Given the high prevalence of stairway falls across the adult lifespan, perhaps more cautious strategies are appropriate for adults of all ages.

Most concerning about falls on stairs is that, when compared to falls while level walking, they represent a disproportionately high risk for mortality or for major injury such as traumatic brain injury (TBI) and hip fracture [7,15]. Twenty-seven percent of fall-related TBIs occur on stairs for young and middle-aged adults [16], and 51% occur on stairs for older adults [17]. Older adults are over 3 times more likely to sustain a moderate-to-severe TBI when falling on stairs as compared to when falling while walking [18]. In addition, use of stairs is a significant predictor of hip fracture over other fall-related injuries for older adults [19].

Therefore, the epidemiologic data suggest that fall risk is often predicted by personal, environmental, and task-related factors. Stairway falls appear to represent a high proportion of falls, particularly for middle-aged adults, and result in a disproportionately high risk of death or of severe injuries known to result in long-term disability and high economic costs.

3. Kinesiologic studies of stair negotiation

In this section, we now transition from epidemiologic studies that help identify the circumstances and consequences of stairway falls to kinesiologic studies that help to understand how person-related, environmental and task-related factors affect stair negotiation. Such studies can then provide insights into why factors associate with stairway falls and how to potentially intervene on these factors.

In the years 1997 and 2000, Cavanagh and coworkers [7,20] presented reviews of stair negotiation in older adults, and the authors highlighted the relevance of falls on stairs for this population. The authors also presented a call for basic science and biomechanical evaluations that systematically test stair and handrail architecture as well as lighting and visual surround, using measures of foot clearance, foot placement, joint range of motion, center-of-mass displacements, as well as joint moments, powers and capacities. This call for research has been largely accomplished in the nearly two subsequent decades. Biomechanical studies have evaluated stair negotiation of healthy young and older adults with manipulations of stair architecture, handrail use, lighting, cognitive dual tasking, and movement strategies. These studies have also spanned evaluations of many measures derived from kinematics, kinetics, and inverse dynamics. Some investigations have also been employed on people with specific health conditions. The remainder of Section 3, therefore, represents a review of these accomplishments, synthesizing literature on stair negotiation by healthy young adults, then healthy older adults, and lastly on people with health conditions.

3.1. Stair negotiation of healthy young adults

In healthy young adults, many studies have descriptively characterized stair negotiation, including some comparisons of stair ascent, descent, and level walking [21–36]. In sum, these studies demonstrate that the muscle, force, and movement patterns of stair negotiation differ from level walking and that stair negotiation increases the muscle, force and movement demands on the knee and ankle compared to level walking. The coordination of the head is also altered, such that stair descent renders increased sagittal head and neck excursions and a more synchronized in-phase coordination with the trunk compared to stair ascent or level walking [37]. Stair negotiation is also clearly a risky endeavor, as foot clearance is both variable and often less than a centimeter from the stair surface, particularly at the initial steps [38,39]. Low and variable foot clearance risks the foot

scuffing the stair and causing a person to trip. In addition, required coefficients of friction generated during stair use are also variable, reaching maximum reported values of about 0.7 [40,41]. Therefore, stair use not only risks tripping due to low and variable foot clearance, but also risks slipping due to high surface-friction demands. Knowing these requirements on motor precision and control during stair use, it becomes easy to see how the risky behavior choices identified in Section 2 strain an already challenging task to elicit stairway falls.

3.1.1. Stair negotiation of healthy young adults: person-related factors

Kinesiologic studies have evaluated the effects of person-related factors on stair negotiation in healthy young adults by experimentally manipulating their functional capabilities. For example, loading the trunk with an additional 20% body weight increases knee moments [42]. Such loading could have long-term health consequences that are relevant to conditions of chronic loading such as in the workplace, military, or school settings, and the findings may also be relevant to issues pertaining to stair use by people with obesity. Protocols that physically fatigue subjects appear not to affect stair ascent [43,44] and have differing outcomes on descent, such that time to completion or joint range of motion may go unchanged [44], but decreased joint displacements and diminished stability of the center of mass relative to the base of support during descent have been reported [43]. Thus, the literature is not definitive to render any recommendations on stair use while fatigued. Further, experimentally restricting visual angle and acuity with goggles increases stance and double-support times [31]. Such effects of experimentally impaired vision on stair negotiation are consistent with the relevance of visual impairment on falls in general [45] and highlight the importance of adequate vision correction on falls. Lastly, experimentally restricting knee motion with a brace or wearing high-heeled shoes can also slow stair negotiation with increased double-support times [31,46]. Collectively, these insights imply a need to (a) restrict use of high-heeled shoes during stair negotiation (b) limit heavy load carry, and (c) appropriately treat lower-limb injuries that restrict range of motion as well as visual impairments in order to facilitate safe stair use.

3.1.2. Stair negotiation of healthy young adults: environmental factors

Kinesiologic studies have also evaluated the effects of environmental factors on stair negotiation in healthy young adults by experimentally manipulating stair architecture, handrail design, as well as visual cues and lighting. Changes in stair architecture, such as increasing stair height, have been found to further increase the demand of stair negotiation for young adults through enhanced knee and ankle displacements, moments, and powers, as well as increased muscle activations [42,47]. Increasing stair height or decreasing tread length also decreases center-of-mass stability and time in double support as well as increases ground reaction forces during descent [47,48]. Young and middle-aged adults self-report a subjective preference for stairs with riser heights of 18.3–21.6 cm and tread lengths of 27.9–30.5 cm [49,50], but stability of the center of mass relative to the base of support as well as trunk tilt appear optimized for stair heights of no more than 17.8 cm and tread lengths of 33–35.6 cm [48]. Thus, preferred stair dimensions may not be the same as safe stair dimensions that optimize stability.

Optimal designs and locations of handrails among different user characteristics and stairway pitch angles have also been suggested based on maximal voluntary forces that can be generated while standing next to a rail [51,52]. Dusenberry et al. [51] specifically recommended that a 51-mm round handrail is functionally appropriate, but artistic designs can be accommodated and can provide the benefit of uninterrupted grasp as long as the handrail is

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