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Review

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

Jesse V. Jacobs

Center for Physical Ergonomics, Liberty Mutual Research Institute for Safety, 71 Frankland Rd., Hopkinton, MA, 01748, USA

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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.

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 kinesiologic studies on successful stair negotiation. Many studies of both epidemiologic and kinesiologic 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

E-mail address: Jesse.Jacobs@LibertyMutual.com (J.V. Jacobs).

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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 symmetric, 32–70 mm wide, with a height above the widest portion of the profile less than 19 mm, and a recess on both sides at least 8 mm deep; each recess should achieve this minimum depth within 22 mm below the widest portion of the handrail and extend down at least 51 mm from the top of the handrail. Further, Maki et al. [52] suggest a handrail height of about 0.9–1.0 m in order to optimize the capacity to generate grasp forces. Handrails of these dimensions support the grasp forces needed to recover from a loss of balance on stairs.

In addition to environmental factors of stair and handrail design, visual cues and lighting also appear to be relevant factors to stair negotiation in young adults. Although studies on lighting and visual cues appear to focus on issues of aging (and will be revisited in the sections below), when young adults are evaluated, results show that high-contrast visual cues about a stair's edging can improve step clearance on stairs [53,54].

To summarize, when evaluating stair and handrail dimensions, studies imply that safer stairs require more space to allow for shorter stair heights and longer tread lengths with access to properly located and shaped handrails. In addition, high-contrast visual cues at stair edges are also beneficial to toe clearance. These design suggestions, however, could be in opposition to other motivations, such as maximizing available floor space and aesthetics. Therefore, incentives or legislative controls may be necessary to prioritize safe stair design, although a more direct link of specific aspects of stair architecture to fall risk is needed through future research.

3.1.3. Stair negotiation of healthy young adults: task-related factors

Manipulating task strategies can also affect stair negotiation. For example, stair ascent with an approaching gait versus without an approach increases the demand of stair climbing by increasing sagittal and frontal moments at the knee and hip [55,56]. Climbing every other step decreases cadence while increasing velocity, muscle activation and metabolic cost [57]. In contrast, performing a step-by-step strategy (both feet contact each step) in comparison to a step-over-step strategy decreases peak joint flexion, as well as flexion moments and power, particularly during descent [58]. In addition, when healthy young subjects use a handrail, reflex excitability of the arm muscles becomes enhanced [36] and center-of-pressure velocity increases during ascent, while cadence decreases during both ascent and descent [59]. Thus, the physical demands of stair use appear reduced with pausing at stair transitions, taking a slower step-by-step strategy in which both feet contact each step, and maintaining contact with a handrail.

Distracted attention represents one other task-related factor that affects stair negotiation. Dual tasking – employing a cognitive-motor task during stair ascent and descent – decreases distal joint displacements while increasing hip displacements and medial-lateral center-of-mass displacements [60]. Dual tasking also increases step times and impairs performance of the second task [61] as well as decreases loading rates, ankle plantarflexion moments, and toe clearance [62]. These alterations are enhanced during initial transition steps compared to continuous stair negotiation, suggesting enhanced demand for neural resources during transitions [61,62], which is consistent with the tendency to fall at the top or bottom of the stairway and while distracted [7,20]. Thus, stair use requires a healthy young adult's attention, implying stair environments and behavioral choices need to support focused attention on the task of using stairs in order to optimize performance and reduce falls.

In addition to visual cues being an effective environmental feature (see Section 3.1.1 above), it is possible that stair use places unique task-related demands on vision as well. Studies of gaze fixations, however, demonstrate very little association between fixation counts or durations and the use of a stair tread; there are also no differences in gaze fixations between transitional steps and continuous steps, and very little fixation at handrails [61,63,64]. Thus, continuous foveal fixation does not appear necessary for successful stair negotiation and it remains unclear when visual information is processed and what visual information is utilized to control stair negotiation. In addition, the effects of experimentally manipulating other sensory modalities (somatosensory and vestibular input) on stair negotiation remains untested. Thus, the mechanisms of sensory-motor processing during stair negotiation remain to be understood and future study is needed in order to adequately direct sensory interventions.

In addition to a lack of understanding about the mechanisms of sensory-motor control during stair negotiation, strategies for balance recovery on stairs when a slip, trip, or misstep does occur have not been well characterized. In a study that tested 4 healthy young-adult males, Maki et al. [65] sought to understand the forces and effectiveness of handrail use during a loss of balance on stairs. They utilized a dome obstacle placed on the stair below the subjects in order to induce a handrail-grasping strategy instead of stepping strategies. The study identified that pulling forces dominate handrail use at 11–17% of body weight, and that using a handrail decreases (a) the grasp forces needed during a loss of balance, (b) the need for a compensatory step, and (c) falls to the ground, whereas using stairs at distance to the rail can delay grasp latencies. The study by Maki et al., therefore, clarifies the value of handrails to prevent falls and provided the data necessary to form guidelines about handrail dimensions that are sufficient to support the forces needed to prevent a stairway fall [51]. This example demonstrates the potential value of understanding balance-correcting strategies on stairs in order to direct either behavioral or environmental interventions that mitigate falls or their consequences. This study, however, is limited in scope due to the manipulation of the step to induce handrail use as well as the small and homogeneous sample of 4 healthy young-adult males. These findings remain relevant, however, because most users do not use a handrail when available, will descend stairs beyond arm's length from the handrail, and often carry an item so both hands are not free during stair use [66]. Thus, the contrast between the benefits of handrail use and the prevalence of handrail use offers potential to decrease fall risk through interventions that facilitate handrail use. Further study is needed, however, to understand the behavioral and design interventions that best facilitate safe behavioral choices and enable successful recovery from a loss of balance on stairs in order to mitigate stairway falls and injuries.

3.1.4. Summary of findings regarding stair negotiation by healthy young adults

The above review demonstrates that the mechanics of stair negotiation in healthy young adults is well understood under a number of conditions that manipulate stairway architecture, the subject's physical status, or instructed movement strategies. Key lessons learned include knowledge that risky behaviors must be de-incentivized because stair use has a very low margin for error due to small and variable toe clearance that risks tripping as well as high and variable friction demands that risk slipping. Low and variable foot clearance also highlights the need for stairs to be uniform in dimension. The literature further suggests that stair heights and tread lengths may not be optimized for stable stair use, handrails must be available and of specific dimensions to facilitate protective grasping, and visual cues at stair edges are beneficial to foot clearance. Further, health conditions that restrict vision and joint range of motion impair stair negotiation, as does restrictive footwear such as high-heeled shoes. Some coordination strategies, such as stepping so that both feet touch each stair and pausing before transitioning to stair use, can decrease the physical demands of stair use. Lastly, stair negotiation requires attention to optimize performance, thereby implying that stair environments and user behaviors need to facilitate focus of attention when using stairs. Future studies of basic science should investigate the contributions of sensory modalities to motor control during stair use as well as to understand the mechanisms of balance recovery during slips, trips, or missteps on stairs in order to direct environmental and behavioral interventions that reduce fall risk.

3.2. Stair negotiation of healthy older adults

3.2.1. Stair negotiation of healthy older adults: person-related factors

Like the kinesiologic studies that investigate young healthy adults, the mechanics of successful stair negotiation are also well described for healthy older adults. For most studies on stair negotiation of older adults, the primary person-related factor evaluated is age itself, although fear of falling and gender have also been investigated. In specific, compared to young adults, older adults ascend and descend stairs slower, with greater stance or double-support times, and with diminished vertical forces at weight acceptance and push off, but with increased force at mid-stance [41,46,67–77]. Older adults also appear to produce less motion or force at the ankle or knee, but more motion or force at the hip, than young adults [73–75,78]. This decreased motion or forces produced by the ankle or knee may reflect a higher level of antagonistic muscular co-contraction [70,76], suggesting that older age associates with altered coordination in addition to impaired strength. Older adults also exhibit smaller, more variable foot clearance [68,79] as well as larger and faster horizontal center-of-mass displacements with less capacity to control fast vertical displacements of the center of mass [72,76,80]. It should be noted that cautious strategies have been reported in older adults such that velocity decreases, toe clearance increases, required coefficients of friction decrease, and center-of-mass or center-of-pressure displacements appear more stable [40,48,59,81]. Such cautious strategies appear more evident in those with fear of falling or functional impairment [53,59,82,83]. Age-related impairments in stair negotiation also appear more evident in women than in men [72,82–84]. Therefore, older adults appear to be at greater risk for falls on stairs because they negotiate stairs with less stability and at a greater risk for tripping. These findings also suggest that physical interventions for older adults will need to address impaired motor coordination in addition to strength.

3.2.2. Stair negotiation of healthy older adults: environmental factors

Environmental concerns regarding stair dimensions and visual conditions have been evaluated for stair negotiation by older adults. Regarding stair dimensions, older adults have a lower maximum stair height at which they are capable to negotiate [71,85]. Increasing stair height and decreasing tread length diminishes center-of-mass stability and increases the demands of stair negotiation for older adults [48,77,86]. Even at standard heights, stair negotiation requires older adults to perform closer to their maximum capacities of joint range of motion and force production than for young adults [87–89]. Thus, standard stair architecture may not fully accommodate stair use by older adults in order to maximize safety [7]. Therefore, the implied need for lower stair heights and longer stair treads from studies on young adults becomes amplified for older adults.

With regard to visual conditions, although low lighting may not affect required coefficients of friction during stair negotiation in older adults [40], low lighting can decrease step length [53], and because older adults do not increase toe clearance in low-light conditions as young adults do, low lighting also likely increases the risk for tripping in older adults [79]. In contrast, extra stairwell lighting can increase step speed [90] and stair-edge contrast cues can improve foot clearance and center-of-mass stability of older adults during stair negotiation [53,54]. Further, handrail cues can increase handrail use, decrease grasp latencies, and improve grasp accuracy [91]. Thus, sufficient ambient lighting, high-contrast visual cues of stair edges, and cues that focus attention on handrails improve performance during stair use by older adults.

3.2.3. Stair negotiation of healthy older adults: task-related factors

Studies on healthy aging have also manipulated the task requirements of stair negotiation. For example, manipulating the height of a cane does not appear to affect single-step descent in older adults [86]. In contrast, using a handrail can improve cadence, modify the coordination of joint forces, and improve center-of-mass stability during stair ascent or descent [59,92]. In addition, older adults appear to require increased neural resources for stair negotiation relative to young adults, as evidenced by greater dual-task costs [81,93]. Thus, older adults would likely benefit from continuous handrail use and focused attention while using stairs, and these benefits are likely more substantial for older adults than for young adults given the older adults' decreased levels of stability and increased attention demands during stair use.

3.2.4. Summary of findings regarding stair negotiation by healthy older adults

The literature on healthy older adults has well-described the mechanics of successful stair negotiation, whereas the contributions of sensory input to motor control during stair use remain unclear and may be altered with aging. Likewise, age-related changes in strategies to effectively respond to a loss of balance on stairs remain untested. Although diminished maximum capacities for joint range of motion and force production suggest interventions should focus on strength and flexibility training, more complex systems-related interventions may be necessary because exercise interventions focused on level stepping and strength training do not improve stair-gait performance [78]. In addition, age-related changes are evident across more functional domains than just strength, as evidenced by differences in motor coordination, cognitive dual-task costs, and effects of visual conditions during stair use. Therefore, laboratory studies need to better understand sensory-motor mechanisms of impairment due to age during stair use and during loss-of-balance events on stairs. Intervention studies ought to provide multi-component sensory-motor and cognitive-motor training to address these complex impairments and should also intervene on the stair environment in order to better accommodate the range of user capabilities across the lifespan.

3.3. Stair negotiation of people with health conditions

Despite the high prevalence of people with chronic health conditions [94] and their known contribution to fall risk [95–106], the relative influence of stairway falls on people with specific health conditions remains unclear. Instrumented biomechanical studies of stair negotiation have been accomplished, particularly on people with stroke, diabetic peripheral neuropathy, or knee pain, and isolated studies on Parkinson's disease and low back pain have also been performed. Thus, the following paragraphs provide a brief review of studies on people with health conditions. This section is organized to focus on the person-related factor of different health conditions and is not organized with sub-sections that detail effects of environmental and task-related factors, because the literature is not sufficiently developed to do so.

3.3.1. Stair negotiation of people with history of stroke

For individuals with history of stroke, the ability to climb stairs without assistance and with a smooth gait pattern correlated with lower-limb muscle strength and standing balance performance [107]. When ascending and descending stairs, regardless of handrail use, people with a history of stroke require a greater amount of force and oxygen consumption relative to maximum capacity than healthy control subjects [108]. Individuals with history of stroke negotiate stairs with slower cadence, diminished lower-limb extensor and hip abductor moments on the more affected side, and increased limb asymmetries when using a handrail [109]. The results, therefore, suggest that stair negotiation could be improved with interventions that improve muscle strength, aerobic capacity and lower-limb coordination during stair negotiation. The use of handrails could exacerbate impaired use of the affected limb with no benefit to the strength or aerobic cost of stair negotiation – although benefits of handrail use to stability or in the event of a loss of balance could be evident and remain untested.

3.3.2. Stair negotiation of people with obesity

Individuals with obesity exhibit more compensatory behaviors (hesitance, handrail use, step-by-step strategies) during stair ascent and descent than individuals who are overweight or of normal weight [110]. Children with obesity exhibit larger hip-abduction and knee-extension moments during stair ascent; smaller hip-extension moments, but larger hip-flexion and knee-extension moments are evident during stair descent [111]. Thus, obesity appears to modify strategies of stair use with consequences on the relative loads placed on joints that have the potential to enhance injury risk. There remains little understanding, however, about the consequences (good or bad) of these obesity-related modifications in stair negotiation and further research remains needed on this subject.

3.3.3. Stair negotiation of people with diabetes and peripheral neuropathy

Individuals with diabetic peripheral neuropathy, but not those with only diabetes, exhibit less stable center-of-mass displacements than healthy control subjects during stair ascent and descent [112]. People with diabetes, with or without neuropathy, also exhibit slower stair negotiation with slower rates of force development and delayed or prolonged muscle activation [113]. During stair descent, people with diabetes, with or without neuropathy, also exhibit greater ankle-dorsiflexion moments and decreased hip-extensor moments during weight acceptance as well as greater hip-flexion moments and decreased ankle-plantarflexion moments during propulsion [114]. People with diabetic peripheral neuropathy also exhibit decreased ankle dorsiflexion and prolonged knee-extensor muscle activation during stair ascent as well as decreased ankle plantarflexion and ankle-dorsiflexor muscle activation during stair descent [115]. Thus, diabetes significantly alters the coordination of the hip relative to the ankle during stair negotiation, and peripheral neuropathy additionally associates with diminished stability. These complex, interacting impairments of sensory-motor coordination again imply need for multifactorial interventions that extend beyond strength training.

3.3.4. Stair negotiation of people with knee pain

Individuals with knee pain (primarily patellofemoral knee pain), exhibit larger foot contact area with smaller peak pressure amplitudes during stair descent than individuals without knee pain [116]. People with knee pain also exhibit greater knee-abduction forces but lower knee-extensor moments during stair negotiation [117–119] as well as altered activation of knee- and ankle-related musculature [119–122]. Kinematic findings have been varied across studies, with reports that people with knee pain exhibit similar joint kinematics [117,123] versus other reports that people with knee pain exhibit diminished knee flexion and angular velocity [121,124] and yet others that report increased knee flexion and internal knee rotation as well as increased hip adduction and internal hip rotation [122,125,126]. Differences among studies may be due to the demographic or pain-state characteristics of the subject sample, pacing of the stair gait, stair design and number of steps negotiated, or the specific calculation and timing of the kinematic measurement. Thus, significant research remains needed to understand strategy selection with knee pain given the heterogeneity of their stair-gait patterns, but one consistency appears to be a redirection of forces from extension in the sagittal plane to abduction in the frontal plane. This modification in the plane of forces at the knee could be beneficial to acutely limit pain during stair use but could also be chronically detrimental to joint structures – a speculation that also requires further research.

3.3.5. Stair negotiation of people with low back pain or Parkinson's disease

In addition to the more developed literature on the health conditions identified above, people with low back pain have been found to exhibit decreased lumbar flexion-extension during stair ascent [127]. Further, people with Parkinson's disease exhibit an increased relative contribution of the hip with decreased contribution of the ankle to the total lower-extremity moment during single-step ascent [128].

3.3.6. Summary of stair negotiation by people with health conditions

Multiple studies on a given health condition that provide replicated instrumented biomechanical analyses of stair negotiation are available for only a few health conditions. Therefore, the scientific literature is not sufficiently developed to understand how stair negotiation contributes to falling in people with health conditions, nor is the literature developed to provide a sufficient understanding of the mechanisms of impaired stair negotiation with health conditions in order to inform potential interventions.

4. Review summary

4.1. Lessons learned from the existing literature

Fall risk is often predicted by factors related to the person, environment, and task. 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. Laboratory kinesiologic studies have broadly characterized the mechanics of successful stair negotiation in healthy young and older adults. These studies offer the following lessons (Fig. 1): (1) standard stair heights may not provide an optimal universal design to enable safe stair use among individuals with a broad spectrum of abilities, (2) studies on aging and health conditions suggest that interventions on muscle strength will not be sufficient to mitigate falls because factors related to central motor coordination, cognition, sensation and perception also contribute to impaired stair negotiation, and (3) environmental or person-focused interventions that promote behavioral change to limit hazardous activities on stairs are likely to prevent falls or engender less severe consequences when a fall does occur.

4.2. Suggested needs for future study

4.2.1. Needs for kinesiologic laboratory studies

Future study is needed to better understand sensory-motor mechanisms of control as well as mechanisms of impairment due to age. Very little is also known about successful versus unsuccessful recovery strategies from a loss of balance on stairs.

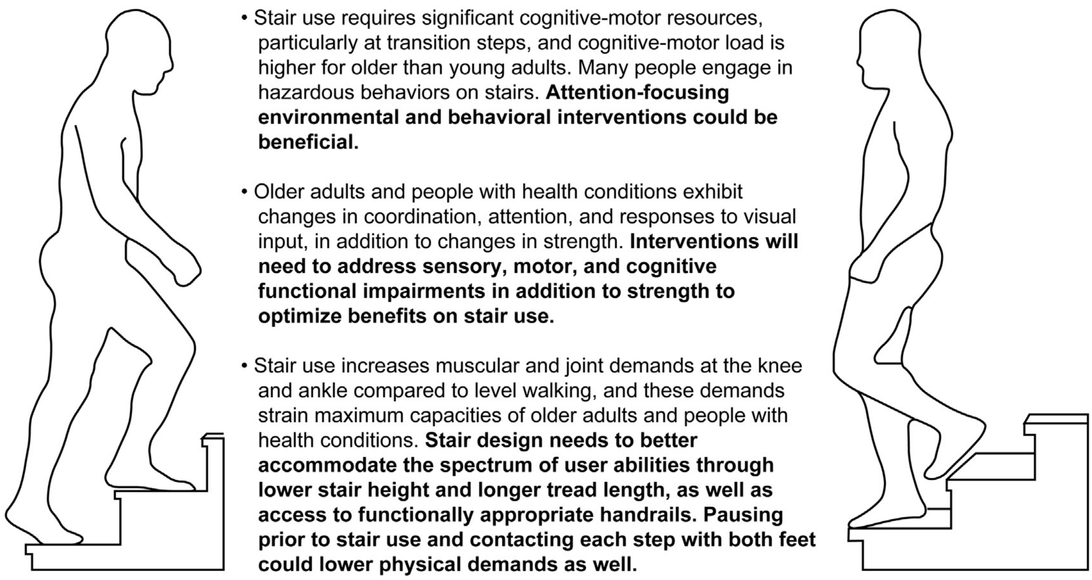

Fig. 1. Primary outcomes from the existing literature on stairway falls and stair negotiation (regular text) and potential lessons learned from this information (bold text).

Despite the high prevalence of health conditions in society and their contribution to fall risk, the literature is not well developed to understand the relevance of stair negotiation to falls in people with health conditions nor are the mechanisms of impaired stair negotiation in people with health conditions well understood. Thus, future kinesiologic studies would benefit from a focus on sensory-motor mechanisms of control as well as understanding strategies for recovery from a loss of balance on stairs across populations of differing ability due to age or health conditions. Understanding the sources of impairment will inform evidence-based interventions on stairway environments, education programs, and physical exercise programs.

4.2.2. Needs for kinesiologic studies outside the laboratory

Sections 3.1 to 3.3 review laboratory-based kinesiologic studies of stair negotiation, but new technologies in wearable motion sensors have the potential to inform the scientific literature with greater ecological validity than ever before. Recent studies have demonstrated that inertial motion sensors are capable of recording joint angles during stair use with acceptable accuracy compared to laboratory motion capture systems (on average, a 4-degree error) [129]. Such sensors are also capable of differentiating and classifying stair use versus other activities, even when measured by a cell phone in a pants pocket, although some confusion with level walking remains a concern [130]. Age-specific classifiers may also be needed in order to maintain accurate activity classification [130]. Although the algorithm was somewhat specific to the tested staircase, higher levels of classification accuracy have been reported across individuals of differing physical ability when using a more specified sensor connected to a neck-worn lanyard in addition to using a cadence-scaled threshold in data processing [131]. Interestingly, the same study [131] utilized the sensor signals to evaluate the quality of stair-use performance and found that the signals correlated with demographics, clinical measures of function, and future falls. Thus, further development on the use of wearable sensors during daily activities is needed to identify the most optimal balance of user-friendly sensor placement, choice of sensor, and accurate classification algorithms across a population of differing abilities. With this future development, wearable sensors have the potential to enable remote classification and assessment of ecological stair use. Such insights could provide timely, objective input to identify locations or individuals at risk for stairway falls in order to then intervene on these risks and mitigate falls.

4.2.3. Needs for intervention studies

Knowledge from the suggested kinesiologic studies could be used to direct diagnostics for identifying people or locations at high risk for falls in order to then intervene on these risks and reduce stairway falls and injuries. Interventions may include modifying the environment (stair structure and surfaces, handrails, visual cues, distractors), programs that promote behavior change to reduce risky choices while using stairs, as well as multifactorial medical care and sensory-motor and cognitive-motor physical exercise in order to improve physical and cognitive function and enable improved stair-gait performance. To date, falls prevention programs do appear to reduce falls, but these programs are often focused on the older adult and on person-related factors such as health and physical function [132]. Even multi-component trials largely focus their intervention on physical function [133]. Although some programs of environmental assessment and modification have been found to improve fall risk [132,134], these results are not consistent [135]. Thus, optimal, multi-component intervention studies remain needed, and the relative benefit of these multi-component intervention strategies on stairway falls also requires clarification.

Implementing such interventions may present challenges regarding cost, unclear loci of responsibility for their implementation, legislative controls, and limited available time and skilled practitioners to implement such programs [136]. Future study, therefore, will need to determine the viability, safety, and efficacy of large-scale intervention programs that test novel implementation approaches. Given the significant burden of stairway falls on societal health and financial well-being, there is a high level of potential that future study on optimal risk detection, intervention, and implementation approaches will ultimately generate improved outcomes of decreased stairway falls and injuries for a safer, healthier society.

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Conflict of interest

None.

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