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Interventions to Promote More Effective Balance-Recovery Reactions in Industrial Settings: New Perspectives on Footwear and Handrails

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Abstract: "Change-in-support" balance-recovery reactions that involve rapid stepping or reaching movements play a critical role in preventing falls. Recent geriatrics studies have led to new interventions to improve ability to execute these reactions effectively. Some of these interventions have the potential to reduce fall risk for younger persons working in industrial settings. In this paper, we review research pertaining to two such interventions: 1) balance-enhancing footwear insoles designed to improve stepping reactions, and 2) proximity-triggered handrail cueing systems designed to improve reach-to-grasp reactions. The insole has a raised ridge around the perimeter that is intended to improve balance control by providing increased stimulation of sensory receptors on the footsole in situations where loss of balance may be imminent. The cueing system uses flashing lights and/or verbal prompts to attract attention to the handrail and ensure that the brain registers its location, thereby facilitating more rapid and accurate grasping of the rail if and when sudden loss of balance occurs. Results to date support the efficacy of both interventions in geriatric populations. There is also some evidence that these interventions may improve balance control in younger persons; however, further research is needed to confirm their efficacy in preventing falls in industrial settings.

Key words: Aging, Falls prevention, Footwear, Handrails, Postural balance, Slips, trips and falls, Stair safety

Introduction

Historically, there has been relatively little "cross-pollination" between geriatrics research aimed at preventing falls in older adults and safety-science research aimed at preventing slips, trips and falls in industrial settings. We propose, however, that there is potentially much to gain by applying similar intervention approaches in both contexts. In both situations, the fundamental prerequisites for a fall remain the same: there must be an initial "loss of balance" (precipitated by a balance perturbation such as a

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slip, trip, misstep or collision) and there must be a failure of the balance-recovery mechanisms to counteract the destabilization[1, 2]. Hence, an intervention that either reduces the likelihood of experiencing a perturbation or improves the ability to respond to the perturbation should help to reduce the risk of falling, regardless of the setting.

Typically, in older adults, the risk of falling is elevated due to age-related impairments in the neural, sensory and/or musculoskeletal systems. In the industrial setting, the risk may be elevated, in younger persons, due to hazards in the work environment (e.g. slippery surfaces, trip hazards)[3] and/or the need to perform distracting or destabilizing tasks while standing or moving about. Middle-aged and older workers may suffer the "worst of both worlds", i.e. the need to meet challenging work-related balance demands in the face of age-related balance impairment. This is supported by occupational-injury studies, which indicate that older workers report higher rates of "slip, trip and fall" incidents[3]. Although the vast majority of balance research has focussed on "young adults" (e.g. 20–30 yr) and "older adults" (e.g. 65 and older), age-related deterioration in the neural and sensorimotor systems that sub-serve balance control often begins to manifest around the age of 40–50[4, 5]. Furthermore, some of the few balance studies that have included a middle-aged group (e.g. 35–55 yr) have, in fact, found evidence of altered balance control[6]. Hence, middle-aged workers may represent an "at-risk" group that has been largely neglected in the balance-control literature.

Although the causes of falling are varied and complex, a critical factor that ultimately determines whether a slip, trip or other perturbation leads to a fall is the ability to execute effective balance-recovery reactions[2]. Balance recovery involves regulating the relationship between the center-of-mass of the body and the base-of-support[7]. The center-of-mass motion can be decelerated by rapidly generating muscle torque at the ankles, hips or other joints; however, a much greater degree of stabilization can be achieved by rapidly changing the base-of-support[8, 9]. These "change-in-support" reactions involve initiating a step, modifying a step in progress, or reaching to grasp or touch an object for support. Because of the biomechanical advantages, compensatory stepping and reaching play a vital functional role in preventing falls. They are the only recourse in responding to large perturbations, but they are also prevalent even when the perturbation is relatively small[8, 10].

Change-in-support reactions are initiated and executed much more rapidly than even the fastest volitional limb movements[8, 11, 12], yet the control is remarkably sophisticated. In contrast to volitional movement, where there is the opportunity to preplan the movement, successful execution of these compensatory reactions must take into account the unpredictable body motion suddenly induced by the perturbation, as well as the constraints on limb movement imposed by the environment (the location of objects to grasp and obstacles to avoid)[13–15]. The capacity, in daily life, to detect onset of instability and to rapidly plan and execute an effective stepping or reaching reaction may be further complicated by effects of ongoing physical or cognitive activity[15–19]. Older adults may be at increased risk of falling if they are unable to meet these various demands for executing effective change-in-support reactions, as a consequence of age-related deterioration in the neural, sensory and/or musculoskeletal systems[2, 8, 9]. A number of studies have, in fact, identified age-related impairments in the control of specific aspects of change-in-support reactions and links to increased risk of falling (see Maki *et al.*[20, 21] for recent reviews).

In this paper, we review recent research pertaining to two new interventions that were developed primarily for the purpose of reducing fall risk in older adults: 1) balance-enhancing footwear insoles designed to improve stepping reactions, and 2) proximity-triggered handrail cueing systems designed to improve reach-to-grasp reactions. We first explain the rationale for these interventions and summarize the studies that support their efficacy in geriatric populations. We also summarize the evidence suggesting that these interventions may also improve balance control in younger adults, and conclude by discussing the reasons that these interventions may be beneficial in industrial settings, for workers of all ages. All of the studies by the authors were approved by the institutional ethics review board, in accordance with the Declaration of Helsinki (1983), and all subjects provided written informed consent.

Balance-enhancing Footwear Insetrs

Background

Age-related reduction in cutaneous sensation is very common[22], and has been shown to predict an increased risk of falling[23]. The cutaneous mechanoreceptors on the sole of the foot play an important role in controlling a number of specific aspects of balance[24–27], but appear to be particularly important in providing the central nervous system (CNS) with information pertaining to the stability limits of the base-of-support and the state of contact between foot and ground[28–30]. This information is crucial for the control of stepping reactions; hence, age-related loss of plantar cutaneous sensation may be an important factor contributing to impaired control of compensatory stepping.

To study this, we simulated age-related loss of plantar cutaneous sensation in healthy young adults by means of hypothermic anaesthesia (cooling the foot sole in ice

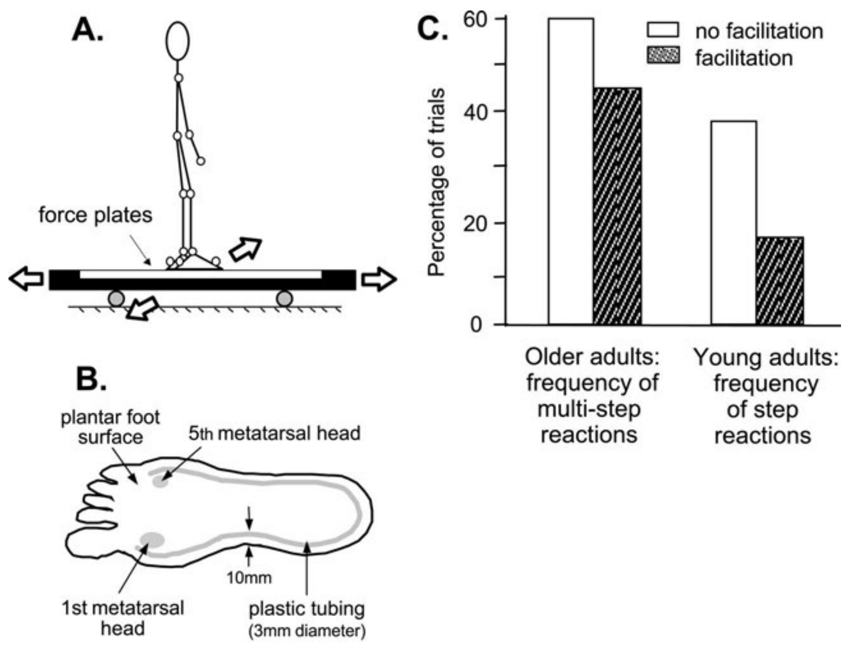

Fig. 1. Effects of facilitation of plantar cutaneous sensation on perturbation-evoked stepping reactions.
A. schematic drawing of the large (2 × 2 m) computer-controlled multi-axis motion platform used to evoke stepping reactions in forward, backward and lateral directions; B. schematic drawing illustrating how tubing was adhered to the perimeter of the foot sole so as to facilitate cutaneous sensation; C. example results illustrating how the facilitation reduced the tendency of older adults to execute multiple steps (and/or arm movements) to recover balance during forward "falls" (p=0.045) and increased the ability of young adults to recover balance without stepping during backward "falls" (p=0.045). Note that the older adults were instructed to react naturally, whereas the young adults were instructed to try not to step. Subjects were blindfolded in all tests. Data are based on 14 healthy older adults (aged 65–73) and seven healthy young adults (aged 23–31)[28)].

water)[29)]. Subjects were blindfolded and postural perturbations were delivered via sudden unpredictable translation of a multi-axis motion platform on which the subjects stood (Fig. 1a). The anaesthesia of the foot sole led to an increased frequency of multiple-step reactions in responding to forward instability, delayed initiation of backward stepping reactions and less frequent use of crossover steps during lateral step reactions. The need to take multiple steps to respond to forward falls appears to be related to impaired ability to sense and control heel-contact and subsequent weight transfer during termination of the initial step. The delay in initiating backward steps likely reflects impaired ability to sense posterior stability limits at the heel. The tendency to avoid lateral crossover steps may reflect difficulty in maintaining stability during the prolonged swing phase required to execute these reactions.

Significantly, the effects of the cutaneous anaesthesia appear to mirror a number of age-related changes in compensatory stepping. Moreover, facilitation of cutaneous sensation in older adults tended to reverse some of these effects[28)]. The facilitation was accomplished by adhering flexible plastic tubing (3 mm in diameter) to the perimeter of the foot sole (Fig. 1b). In placing the tubing around the periphery, our intent was to ensure that the facilitation is most potent in situations where loss of balance is imminent: displacement of the body center-of-mass near the limits of the base-of-support is intended to cause the tubing to indent the skin, thereby increasing stimulation of nearby cutaneous receptors. In responding to unpredictable platform perturbations in various directions (forward, backward, left, right), blindfolded older adults (aged 65–73) executed multiple-step reactions (and/or arm movements) less frequently when the tubing was adhered to the foot sole (p=0.036). This effect was most pronounced during forward loss of balance (Fig. 1c). In addition, the tubing caused a reduction in the backward excursion of the center of foot pressure during feet-in-place (non-stepping) balance reactions evoked by continuous pseudorandom antero-posterior platform motion (p=0.003).

The facilitation due to the tubing also appeared to have some benefits for healthy young adults (aged 23–31). Specifically, the facilitation improved ability of blindfolded young adults to comply with instructions to resist stepping, in responding to platform perturbations evoking backward loss of balance (p=0.045; Fig. 1c)[28)]. As in the older adults, the facilitation also led to a decrease in backward excursion of the center of foot pressure during feet-in-place reactions evoked by continuous pseudorandom antero-posterior platform motion (p=0.013). These results suggest that the facilitation improved ability of young adults to detect the posterior limits of stability at the heel.

Description of the intervention

The intervention is a footwear insert, known as *SoleSensor* (U.S. patent #6.237.256 issued May 29, 2001; commercial release currently scheduled for 2008 by Hart Mobility, www.hartmobility.com), that has a raised compliant ridge around the perimeter (Fig. 2b). Analogous to the tubing used in our facilitation experiments, the ridge is designed to cause indentation of the skin and associated stimulation of cutaneous mechanoreceptors located near the periphery of the sole in situations where loss of balance may be imminent. To prevent skin irritation or discomfort and reduce any potential for habituation to the stimulus, the ridge is constructed of compliant elastomeric material, so that substantive skin indentation and associated mechanoreceptor stimulation occurs only when the center-of-mass nears the base-of-support limits. While other approaches such as vibrating insoles[26)] can also provide enhanced plantar cutaneous sensation, such insoles require a power supply, electronic circuitry and electromechanical transducers. In contrast, the *SoleSensor* is a totally passive insole that is much simpler and less expensive.

Testing of the intervention

An initial clinical trial has been performed to determine the effects of the insole on control of dynamic stability during gait. A second objective was to determine whether the benefits of the insole persist over a prolonged period of daily use (12 wk), or whether habituation occurs. We also wanted to determine whether there are any practical problems associated with wearing such footwear (e.g. discomfort or skin irritation) and to collect some preliminary evidence regarding potential benefits in reducing risk of falling.

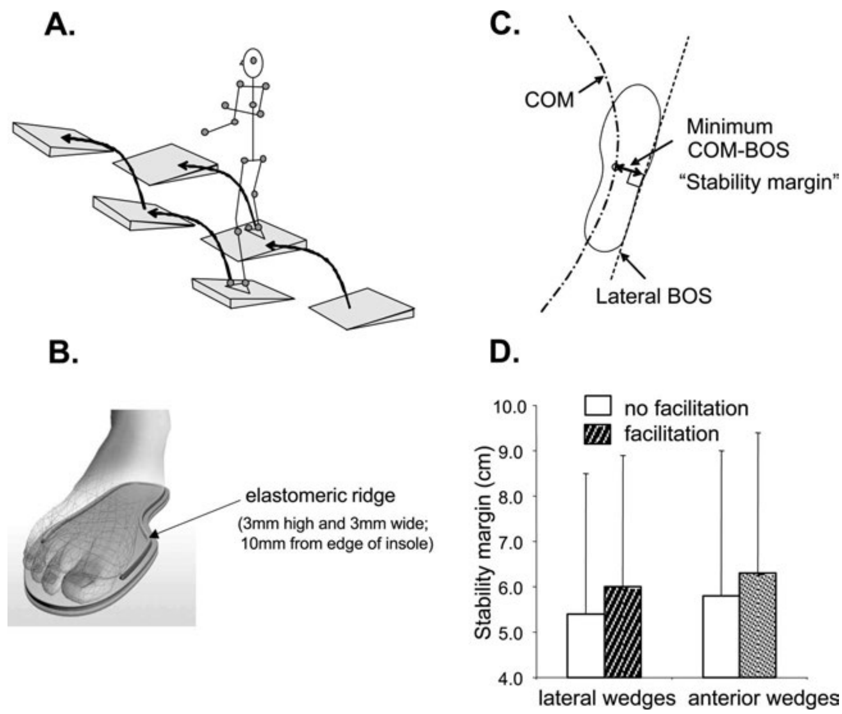

Fig. 2. Effects of facilitation of plantar cutaneous sensation on lateral stability while walking over uneven terrain. A. schematic drawing showing the use of inclined platforms (10-degree inclination) to simulate uneven terrain; B. schematic rendering of the *SoleSensor* insole used to facilitate cutaneous sensation; C. example data showing how lateral stability was quantified in terms of the lateral stability margin, i.e. the minimum medio-lateral distance between the center-of-mass (COM) and the lateral margin of the base-of-support (BOS) during the single-support phase of the gait cycle; D. example results showing how the facilitation increased the mean lateral stability margin in trials where the high edge of the inclined platform was located lateral (p=0.007) or anterior (p=0.035) in relation to the stance foot. The displayed means and standard deviations were based on 40 healthy older adults (aged 65–75) with moderate (non-neuropathic) loss of plantar cutaneous sensation[31, 33, 44)]. The gait tests were performed both before and after a 12-wk period of wearing either the *SoleSensor* (n=20) or a conventional insole (n=20); all subjects were tested with both types of insole in each testing session. The effect of the *SoleSensor* insole was the same in both testing sessions, and did not habituate significantly after wearing the insole for 12 wk.

The details of the clinical trial are provided elsewhere[31–33]. Briefly, the study involved 40 community-dwelling older adults (aged 65–75) with moderate loss of plantar cutaneous sensitivity (unrelated to peripheral neuropathy). Twenty subjects wore the *SoleSensor* for 12 wk and 20 wore a conventional insole. A gait perturbation protocol (walking over uneven terrain) was used to assess dynamic balance control (i.e. lateral excursion of the center-of-mass in relation to the base-of-support; Fig. 2c). Subjects were instructed not to look down at their feet, and the configuration of the inclined platforms used to simulate uneven terrain (Fig. 2a) was varied unpredictably from trial to trial. These tests were performed initially at baseline and were then repeated after subjects wore the assigned insoles for 12 wk. Participants also sent in weekly postcards with information pertaining to insole comfort, hours of wear and occurrence of falls.

The gait trials indicated that *SoleSensor* improved the ability to stabilize the body when walking on uneven terrain, and that this benefit persisted when measured after 12 wk of wearing the insole (Fig. 2d). Furthermore, nine subjects who wore conventional insoles experienced one or more falls over the 12-wk period, whereas only five subjects fell while wearing the *SoleSensor*. Although there were initial reports of discomfort in ten cases, all but one subject tolerated wearing the *SoleSensor*, and 17 of 20 subjects indicated (after completing the study) that they would like to continue wearing the insole on a long-term basis.

Proximity-triggered Handrail Cueing Systemes

Background

In order to reach to grasp or touch an object such as a handrail, the CNS requires visuospatial information about the location of the "target". However, for compensatory reaching reactions that are triggered by sudden unexpected or unpredictable loss of balance, the urgent need to react rapidly places severe temporal constraints on visuomotor processing. Recent results suggest that the CNS initiates these rapid compensatory movements using an egocentric "spatial map" of the immediate surroundings that is formulated prior to perturbation onset and automatically updated on an ongoing basis as the person moves about[14, 15]. This control strategy avoids the delay that would occur if instead it were necessary to construct a map to guide the compensatory movement after the onset of the perturbation. If and when a sudden unexpected loss of balance occurs, the pre-formed map can be used to immediately initiate a very rapid arm movement that is directed toward the nearest available handhold.

The need to monitor the environment suggests a critical role for the processing of visual information, involving various aspects of visual attention, spatial working memory and gaze control, all of which are known to decline with aging[34–36]. In addition, aging may impair ability to disengage attention from an ongoing motor or cognitive task[37]. Although no studies have yet directly examined effects on control of change-in-support balance reactions, it has been shown that common age-related visual-processing deficits can severely impair motor behavior in other situations that require visual monitoring of the surroundings. In particular, driving studies have shown strong links between car-accident risk and decline in the "Useful Field of View" (UFOV), which is a measure of the ability to rapidly extract information from the peripheral visual field[38]. A recent study has also shown that decrease in UFOV is correlated with reduced mobility in older adults[39].

Description of the intervention

The intervention is a cueing system (patent pending) that is intended to automatically and involuntarily draw attention to the handrail for a brief time interval as the person approaches[32, 40]. We propose that this "attention capture" system will help to ensure that the handrail is incorporated into the individual's internal "spatial map" of the surroundings and thereby improve ability to rapidly and accurately reach to grasp the handrail for support if and when a sudden loss of balance occurs. In doing so, this device is intended to compensate for age-related deficits in visual attention and processing that might otherwise have caused a failure to detect the presence of the handrail or to map its location accurately. Although we focus here on handrails, the same principles apply to other safety supports, such as grab-bars, safety poles, hand-grips and handles.

The visual-attention literature suggests that attention capture will be facilitated by locating the cues in close proximity to the rail, and by using cues that have a distinct onset[41]. Attention capture may also be enhanced if the cue has symbolic features that are familiar and meaningful to the user. There are, in fact, certain generic symbols that most people tend to "overlearn" in the course of their daily lives, and there is strong evidence that the appearance of an overlearned symbol in the visual field will produce an involuntary shift of attention[42]. In the context of a handrail cueing system, use of green or yellow flashing lights, for example, may draw attention to the rail by taking advantage of overlearned associations with traffic lights and safety.

Based on these considerations, we have developed a handrail cueing system in which green or yellow light-emitting diodes (LEDs), mounted internally along the longitudinal axis of a translucent railing, are triggered by a photoelectric proximity-sensor to suddenly begin flashing as the individual approaches the handrail, thereby pro-

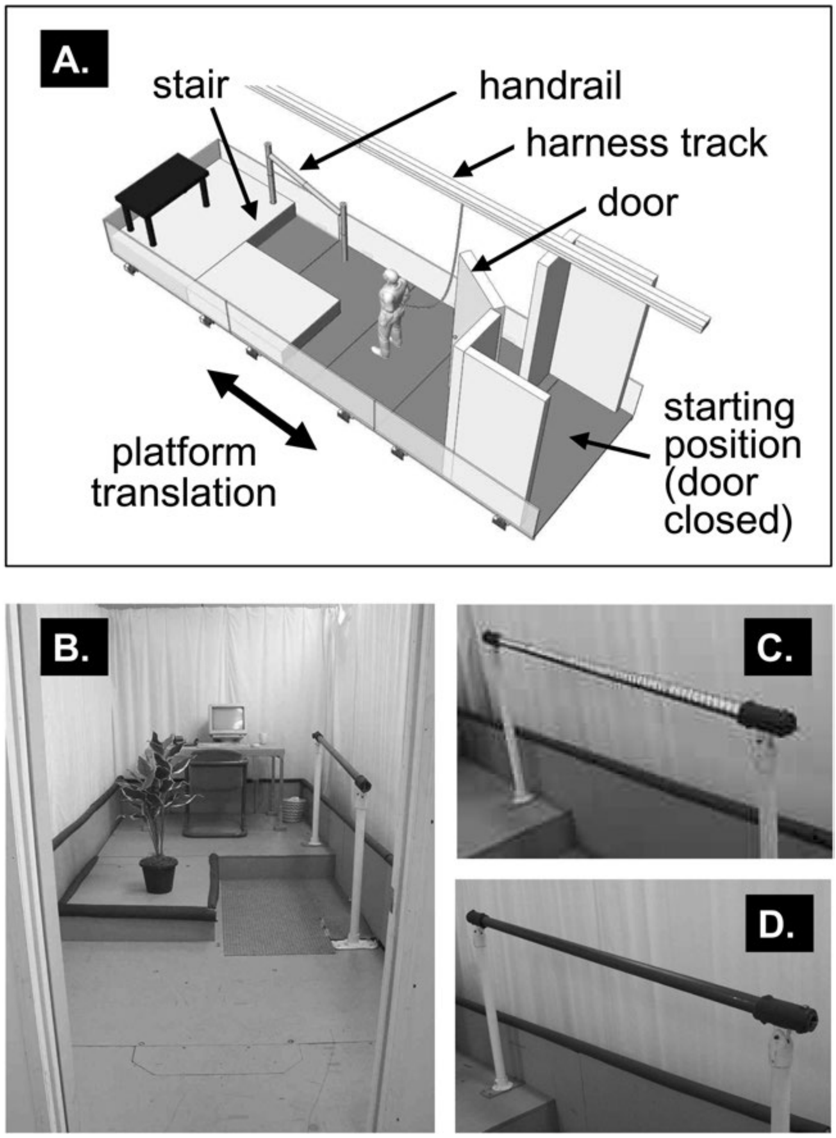

Fig. 3. Schematic drawing (A) and photograph (B) of the large (2 m × 6 m) computer-controlled motion platform used to study the handrail cueing systems (C and D).

Panel B shows a view (through the doorway) of objects mounted on the platform so as to simulate the visual complexity of a typical "real-life" living environment; these objects also serve as visual distracters. The door prevents viewing of the environment prior to the start of the trial. The subject is given the task of making a telephone call, which requires opening the door, performing a visual search for the phone and walking to the far end of the platform to access the phone (located on the table, beside the computer). The platform is triggered to move suddenly, so as to evoke a reaching reaction, when the subject steps on a pressure mat adjacent to the handrail. The handrail cueing is triggered by a photocell to begin ~2s before the subject arrives at the rail; during visual cueing, yellow or green LEDs mounted within the translucent rail are controlled to flash on (C) and off (D). Adapted from Maki *et al*.[44)] and Scovil *et al*.[40)].

viding an abrupt onset cue (Figs. 3c, 3d). The railing itself is black, so as to enhance visibility of the LEDs. This also provides high contrast with typical surroundings (e.g. white walls), which may facilitate grasping by improving ability to delineate the contours of the railing. Although a black rail may be sub-optimal under dark conditions, the flashing LEDs will help to ensure that the rail is visible. A flashing frequency of 3 Hz was selected to promote attention capture, while minimizing any potential danger to those at risk of photic-induced seizures[40)].

A second version of the cueing system delivers a prerecorded verbal prompt (e.g. "attention, use the handrail") that is also triggered by the proximity sensor and delivered by audio speakers built into the handrail mounting fixtures. The verbal prompt may be delivered alone, or in combination with the visual cueing. We expected that the combination of visual and auditory cues would enhance attention capture, given the evidence that congruent multi-modal stimuli are more effective in influencing behavior than stimuli that involve a single sensory modality (particularly so in older adults)[43]. As detailed previously[40], characteristics of the auditory cue were selected on the basis of ergonomic literature on the optimal design of warning systems: 1) sound level >15 dB above background noise; 2) speech (rather than an abstract tone); 3) female voice; 4) use of a signal word ("attention"); 5) urgent tone; and 6) length (4–6 words) and number of repetitions (two) of the phrase.

Our primary intention in adding the verbal prompt is to enhance involuntary attention capture. In addition, however, the prompt may influence voluntary behavior by encouraging the person to hold the handrail before loss of balance can occur. In terms of maximizing safety, this is actually the most desirable outcome; however, we anticipate that this effect will not occur consistently. Furthermore, the verbal prompt may be too disruptive or distracting to be used in some environments. The influence of the visual cueing on the control of subsequent change-in-support reactions is expected to be a much more consistent and robust benefit. By momentarily capturing attention, the cueing may help to ensure that the rail is incorporated into the individual's "spatial map", and thereby facilitate rapid and accurate grasping of the rail in response to a subsequent unexpected loss of balance.

Testing of the intervention

The protocol used to test the handrail cueing systems[32, 40, 44, 45] involves an extended (2 m × 6 m) motion platform that is configured to simulate a realistic living environment, including a stair, a handrail and various visual distracters (Figs. 3a, 3b). The platform is triggered to move suddenly when the subject steps on a pressure mat adjacent to the handrail, and a deception is used to ensure that this perturbation is truly unexpected (subjects are made aware that the platform is capable of moving, but are told that it will not move in this "initial practice trial"). To prevent learning and adaptation, subjects perform only one trial, which is their very first exposure to the perturbation and environment. A door prevents viewing of the environment prior to the start of the trial. The subject is asked to perform a task that simulates a typical activity of daily living: making a telephone call (or, in some initial pilot tests, answering a ringing phone). This requires opening the door, performing a visual search for the phone and walking to the far end of the platform to access the phone. The handrail cueing is triggered by a photocell when the subject is 1.4m from the rail, ensuring that the subject is exposed to the cueing for ~2s before arriving at the rail. Effects of the cueing systems are assessed by using a head-mounted eye tracker to record gaze behavior (e.g. timing and duration of gaze shifts toward the rail, visual angle between the point of gaze and the rail) and a video motion-analysis system to record reaching behavior (e.g. frequency of rail use, timing of rail contact, errors in grasping the rail).

Three cueing conditions were assessed during initial pilot tests: 1) visual cue (flashing yellow LEDs), 2) verbal cue ("attention, use the handrail"), and 3) no cue (conventional handrail). Ten healthy, community-dwelling older adults (OA) aged 57–70 and eleven young adults (YA) aged 20–35 were assigned to one of these three conditions. In initial tests, ten subjects (7 YA, 3 OA) performed the "telephone task" described above without balance perturbation (i.e. the platform did not move). Following these tests, 11 new subjects (4 YA, 7 OA) were tested using various perturbation magnitudes and directions.

The pilot results[40] indicated that grasping of the rail (when walking for the first time in the unfamiliar environment) occurred more often when there was a verbal cue (4 of 6 subjects) or visual cue (2 of 5 subjects), in comparison to a conventional rail with no cueing (1 of 10 subjects). Gaze was measured for 18 (10 YA, 8 OA) of the pilot subjects. Subjects were most likely to look at the rail when there was a verbal cue (4 of 6 subjects) or visual cue (2 of 4 subjects); however, a sizeable proportion of subjects also looked at the conventional rail (3 of 8 subjects). Of the five subjects who grasped the rail (and had gaze data), only two looked directly at the rail before grasping it, suggesting that the other three were able to locate the rail using peripheral vision.

Comments from the pilot subjects raised some concerns regarding use of yellow cue lights. For example, the flashing yellow lights could be interpreted as a warning to avoid using the handrail or stairs. To evaluate such problems, 12 subjects were asked about their perceptions of the yellow cue lights, in comparison to green lights, after completing platform-perturbation trials with both colours. We selected LEDs with a wide viewing angle (90 degrees) and tested the brightest LEDs available in each color (5,000 mcd for green, 2,500 mcd for yellow). Subjects tended to prefer the green LEDs aesthetically, perceived them to be brighter and were more likely to think that they encouraged use of the rail[40]; therefore, we elected to use green LEDs in the main study.

The main study is now in progress. Healthy, community-dwelling older adults are randomly assigned to one of three cueing conditions: 1) visual cue (flashing green LEDs), 2) concurrent presentation of this visual cue and a verbal cue ("attention, use the handrail"), and 3) no cue. Each subject performs a single trial, and is subjected to the unexpected balance perturbation while performing the "telephone task", as described above. The same perturbation direction (forward platform translation) and magnitude is used for all subjects.

Although further testing is required to establish statistical significance, results to date (based on 23 subjects, aged 64–80)[45] appear to indicate the following trends: 1) visual-plus-verbal cueing increased visual fixation of the handrail before and after perturbation onset (Fig. 4a); 2) visual-plus-verbal cueing increased the tendency to hold the handrail prior to perturbation onset (Fig. 4b); 3) both cueing conditions reduced the tendency to make grasping errors (Fig. 4c) and led to more rapid grasping of the rail in reaction to the perturbation (Fig. 4d). The no-cue subjects were less likely to visually fixate the rail, relying instead on peripheral vision to locate the rail. Only one subject who fixated the rail made a grasping error, whereas the remaining five grasping errors all occurred in subjects who did not fixate directly on the rail prior to perturbation onset.

These preliminary results support the viability of handrail cueing as a new intervention to reduce risk of falling; however, larger numbers of subjects must be tested in order to establish whether the preliminary trends are statistically significant. It will also be important to establish that the cueing has no adverse effects, e.g. startle reactions or distracting effects that might actually increase risk of falling. One potential concern is that a prolonged redirection of attention to the handrail could interfere with ability to detect trip hazards or to plan negotiation of a stair; however, results to date indicate that visual fixation of the rail tends to be very brief (e.g. 130–300 ms). If warranted by the final results of our studies, future efforts will be directed at commercialization of the handrail cueing system. As noted earlier, we anticipate that similar cueing systems could be used to draw attention to grab-bars and other safety-enhancing objects. In addition to promoting "spatial awareness" of safety-enhancing objects, there is the potential to use similar cueing techniques to promote involuntary attention capture and spatial mapping of safety hazards that should be avoided.

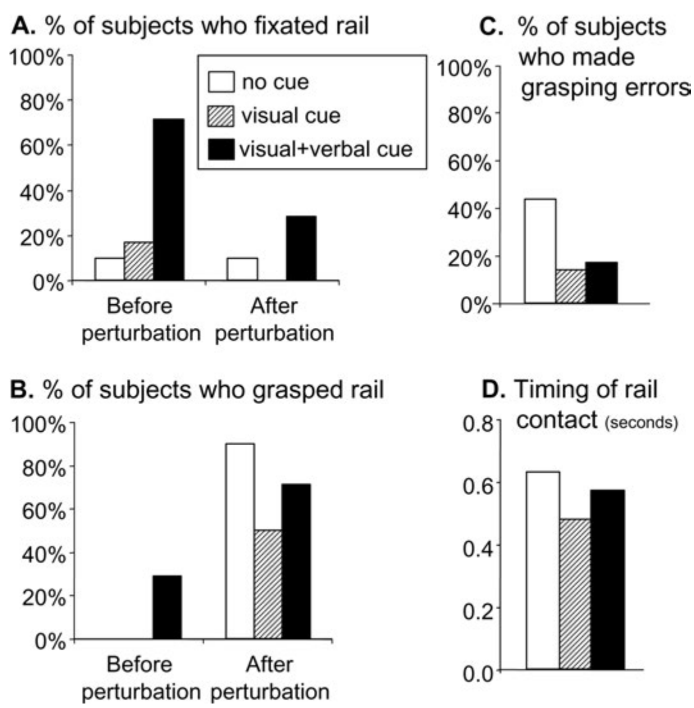

Fig. 4. Preliminary results[45] from the main study being performed to evaluate the efficacy of the handrail cueing systems, using the experimental set-up depicted in Fig. 3.

Panels A-C indicate the percentage of subjects who: A. made one or more saccades to the handrail (before and/or after perturbation onset); B. initiated a reach-to-grasp reaction (before or after perturbation onset); and C. made an error (overshoot or collision of hand with rail) when attempting to grasp the handrail. Panel D displays the mean intervals between onset of platform acceleration and time of handrail contact, for trials where subjects grasped the rail after perturbation onset. The displayed data are based on one trial per subject (very first exposure to the environment and perturbation) for the 23 older adults (aged 64-80) tested to date. Results are shown separately for the subjects who were tested with the visual cue (n=6), the combined visual-plus-verbal cue (n=7), or no cue at all (n=10). Note that the relatively small number of subjects tested to date precludes meaningful statistical analysis.

Discussion

The findings described above support the view that the insole and handrail interventions may help to reduce fall risk by improving the control of balance-recovery reactions that involve rapid stepping or reaching movements. To our knowledge, no other fall-prevention approaches have targeted a specific type of balance-recovery reaction in this manner. We propose that it is crucial to target change-in-support reactions, because the ability to rapidly and effectively alter the base-of-support is the final line of defense that will ultimately determine, in many situations, whether a loss of balance leads to a fall. It appears that the interventions may also provide benefits that generalize to other aspects of balance control, as evidenced by the effect of the insole on dynamic lateral stability during gait.

The primary emphasis of the studies performed to date has been on countering effects of age-related balance impairments in persons aged 65 and older. However, there is some evidence that these new interventions may also provide benefit for younger persons. As noted earlier, the facilitatory effect of the tubing placed around the perimeter of the insole did appear to improve ability of healthy young adults to detect their posterior limits of stability[28]. In addition, studies of young-adult athletes have suggested that the increased sensory feedback provided by a textured insole may enhance performance and reduce risk of injury during sports[46]. For the handrail cueing intervention, pilot testing performed during the development stages indicated that both young and older adults were more likely to grasp the handrail in trials where verbal prompts and/or visual (flashing light) cues were delivered[40].

The difficulties faced by older adults in executing effective stepping and reaching reactions presumably arise as a consequence of age-related impairment in the neural, sensory, motor and/or musculoskeletal systems[2, 20, 21]. Age-related loss of sensation from the sole of the foot is particularly relevant to the insole intervention, whereas age-related attentional deficits are most directly relevant to the handrail intervention. With regard to the latter, older adults appear to be more reliant than younger persons in using attention and other high-level cognitive processing to control balance[47, 48], yet are less able to rapidly disengage attention from an ongoing task and re-allocate attentional resources to the task of maintaining balance[49]. Preliminary evidence from our ongoing studies suggests that older adults may be less likely to detect the presence of salient objects such as handrails when ambulating in an unfamiliar environment, and hence may be forced to rely on "online" visual control to guide the hand toward the rail subsequent to sudden loss of balance[50]. Such reliance on "online" visual feedback could conceivably lead to delays and errors in grasping the rail, which could in turn jeopardize the ability to recover equilibrium.

Such problems will be directly relevant to persons who continue to work past the age of 65. In addition, evidence that age-related deficits such as these begin to develop around the age of 40 would suggest that middle-aged persons who are still active members of the workforce may experience similar difficulties in executing rapid stepping and reaching reactions. However, to our knowledge, there have been no studies of stepping and reaching reactions in middle-aged persons. Clearly, more research is required in this area, to establish whether this population exhibits control problems similar to those that have been demonstrated in older cohorts, and whether the insole and handrail interventions are effective in counteracting such problems.

The interventions may be effective in reducing the risk of industrial falls, even in the absence of age-related balance impairment, due to the fact that the task of controlling balance in the workplace may place heightened demands on the balance-control mechanisms, in comparison to typical residential environments. For example, common workplace hazards such as slippery surfaces may increase the likelihood of experiencing balance perturbations. In addition, the need to engage in work-related cognitive and motor tasks while standing or walking may impair ability to monitor the environment and to re-allocate cognitive resources to the task of balance recovery, should a sudden loss of balance occur. It is also possible that the footwear that is used in certain industrial settings may impair ability to accurately sense pressure on the sole of the foot, and thereby interfere with stepping reactions in a manner that is analogous to the effects of age-related loss of cutaneous sensation.

Although workers are commonly trained to always maintain contact with handrails (e.g. as part of the "3-point contact" method), it is likely that workers may sometimes fail to follow this procedure, particularly if they are distracted, if they are entering a complex or unfamiliar environment where the location of the handrails may not be immediately evident, or if they have not received adequate safety training. The handrail cueing system is expected to provide an additional margin of safety in such situations, by automatically attracting attention to the handrail and thereby increasing the likelihood that the person will either hold the rail or be able to rapidly grasp it in reaction to a sudden loss of balance.

In conclusion, there is considerable evidence to date that supports the utility of the *SoleSensor* insole and handrail cueing system as viable interventions to improve control of balance and reduce risk of falling in persons aged 65 and older. Results from both laboratory testing and a clinical trial have established balance-enhancing benefits of the insole, and have shown that it is well-tolerated by older adults over a prolonged (12-wk) period of daily use. For the handrail-cueing system, trends in the preliminary results support the efficacy of this intervention in older adults; however, completion of ongoing studies is needed to establish statistical significance, and further study will be needed to determine the effectiveness of the system in "real-life" settings. Importantly, there is reason to believe that the insoles and cueing systems may also be effective interventions to increase safety in the workplace, by helping younger persons deal with the heightened attentional demands and other challenges of controlling balance in industrial settings and situations. There is already some evidence that these interventions may be effective in improving the balance of young adults; however, further research is needed to directly examine the effectiveness of these interventions in preventing falls in industrial settings, across the entire age span of the work force.

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