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Preventing falls in older adults: New interventions to promote more effective change-in-support balance reactions

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Abstract

"Change-in-support" (CIS) balance-recovery reactions that involve rapid stepping or reaching movements play a critical role in preventing falls; however, age-related deficits in the neuro-musculoskeletal systems may impede ability to execute these reactions effectively. This review describes four new interventions aimed at reducing fall risk in older adults by promoting more effective CIS reactions: (1) balance training, (2) balance-enhancing footwear, (3) safer mobility aids, and (4) handrail cueing systems. The training program uses unpredictable support-surface perturbations to counter specific CIS control problems associated with aging and fall risk. Pilot testing has demonstrated that the program is well-tolerated by balance-impaired older adults, and a randomized controlled trial is now in progress. The balance-enhancing footwear insole improves control of stepping reactions by compensating for age-related loss of plantar cutaneous sensation. In a clinical trial, subjects wore the insole for 12 weeks with no serious problems and no habituation of the balance-enhancing benefits. The mobility-aid intervention involves changes to the design of pickup walkers so as to reduce impediments to lateral stepping. Finally, work is underway to investigate the effectiveness of handrail cueing in attracting attention to the rail and ensuring that the brain registers its location, thereby facilitating more rapid and accurate grasping.

Keywords: Aging; Assistive technology; Balance training; Falls prevention; Mobility aids

1. Introduction

Although the causes of falling are varied and complex, a critical factor is the ability to respond effectively to balance perturbation (e.g. slips, trips and missteps; collisions or other interactions with the environment; destabilizing effects of volitional movement) (Maki and McIlroy, 2003). Recovery of equilibrium involves regulating the relationship between the center-of-mass of the body and the base-of-support (Pai and Patton, 1997). 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 (Maki and McIlroy, 1997, 1999). 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

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the only recourse in responding to large perturbations, but they are also prevalent even when the perturbation is relatively small (Rogers et al., 1996; Maki and McIlroy, 1997).

Change-in-support (CIS) reactions are initiated and executed much more rapidly than even the fastest volitional limb movements (Burleigh et al., 1994; McIlroy and Maki, 1996b, 1997), 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) (Maki et al., 2003; Ghafouri et al., 2004; Zettel et al., 2005). 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 (Brown et al., 1999; Quant et al., 2001; Brauer et al., 2002; Bateni et al., 2004b; Zettel et al., 2005).

Older adults may be at increased risk of falling if they are unable to meet these various demands for executing effective CIS reactions, as a consequence of age-related deterioration in the neural, sensory and/or musculoskeletal systems (Maki and McIlroy, 1997, 1999, 2003). A number of studies have, in fact, identified age-related impairments in the control of specific aspects of CIS reactions and links to increased risk of falling (see Maki and McIlroy, 2005, 2006 for reviews). Of particular importance is the evidence of impaired control of lateral stability. It is the lateral falls that are most likely to result in hip fracture, which is one of the most serious consequences of falling. Hip fracture often leads to life-threatening complications, immobility and/or loss of independence, and is a major health-care problem (Hayes et al., 1996). In this paper, we provide an overview of four recent initiatives aimed at developing novel interventions to reduce fall risk in older adults by promoting more effective CIS reactions: (1) balance training, (2) balance-enhancing footwear insoles, (3) safer walking aids, and (4) handrail cueing systems.

2. Intervention #1: balance training

2.1. Background

Exercise programs have been found to be most effective in preventing falls when the program involves a strong balance component (Province et al., 1995; Campbell et al., 1999; Rubenstein et al., 2000; Lord et al., 2003). Most balance-training programs have focussed on control of balance during volitional movement; however, it is the ability, or inability, to recover from loss of balance (due to external or self-induced perturbation) that ultimately determines whether a fall occurs. As mentioned above, CIS balance reactions play a critical role in this regard; hence, a training program that improves ability to execute effective CIS reactions could potentially have a profound effect in reducing risk of falling.

In view of evidence that the neural control of volitional limb movements differs in some fundamental ways in comparison to reactions that are evoked by postural perturbation (Maki and McIlroy, 1997, 2005), it can be argued that the most effective training approaches will involve the use of perturbations. A clear example to support this view pertains to the control of lateral stability during forward and backward stepping. During volitional stepping, anticipatory postural adjustments (APAs) act to preserve lateral stability by shifting the center-of-mass toward the stance leg before lifting the swing foot. In contrast, during forward and backward compensatory steps, these APAs are typically absent or severely truncated (McIlroy and Maki, 1993, 1999). As a result, the body falls laterally toward the unsupported side during the step and this lateral falling motion must be arrested during the landing phase. Training volitional stepping might lead to improved control of the APA but would probably not improve control of lateral stability during compensatory stepping.

In recent years, perturbation-based training of CIS reactions has begun to receive attention (Maki and McIlroy, 1999, 2005, 2006; Rogers et al., 2003; Jöbges et al., 2004; Shimada et al., 2004; Protas et al., 2005). To date, four studies have used perturbations to train stepping reactions; however, two of these focussed on Parkinson's Disease (Jöbges et al., 2004; Protas et al., 2005). The other two studies showed potential to improve volitional reaction time in older adults (Rogers et al., 2003; Shimada et al., 2004); however, they did not assess effects of the training on compensatory stepping. No study to date has investigated the potential to use perturbations to train compensatory reaching reactions.

2.2. Description of the intervention

Our perturbation-based training program is described in detail elsewhere (Mansfield et al., 2007). Briefly, this program is aimed at countering age-related impairments in specific features of CIS reactions that have been shown to predict increased fall risk (McIlroy and Maki, 1996a, 2000, 2001, 2005, 2006). The targeted features include: (1) slowing in the initiation and execution of reaching reactions; (2) the tendency to follow an initial forward or backward step with one or more lateral steps; (3) the tendency for the swing foot to collide with the stance leg when stepping laterally. Sudden horizontal motion of a custom-built motion platform is used to evoke CIS reactions during the training (Fig. 1A). These perturbations are administered in an unpredictable manner (variation in timing, magnitude and direction), so as to counter the ability of the central nervous system (CNS) to learn to predict specific features of the perturbation and to use this information to improve the efficacy of the balance reactions (McIlroy and Maki, 1995). This type of predictive control is unlikely to be helpful in responding to the unpredictable perturbations that

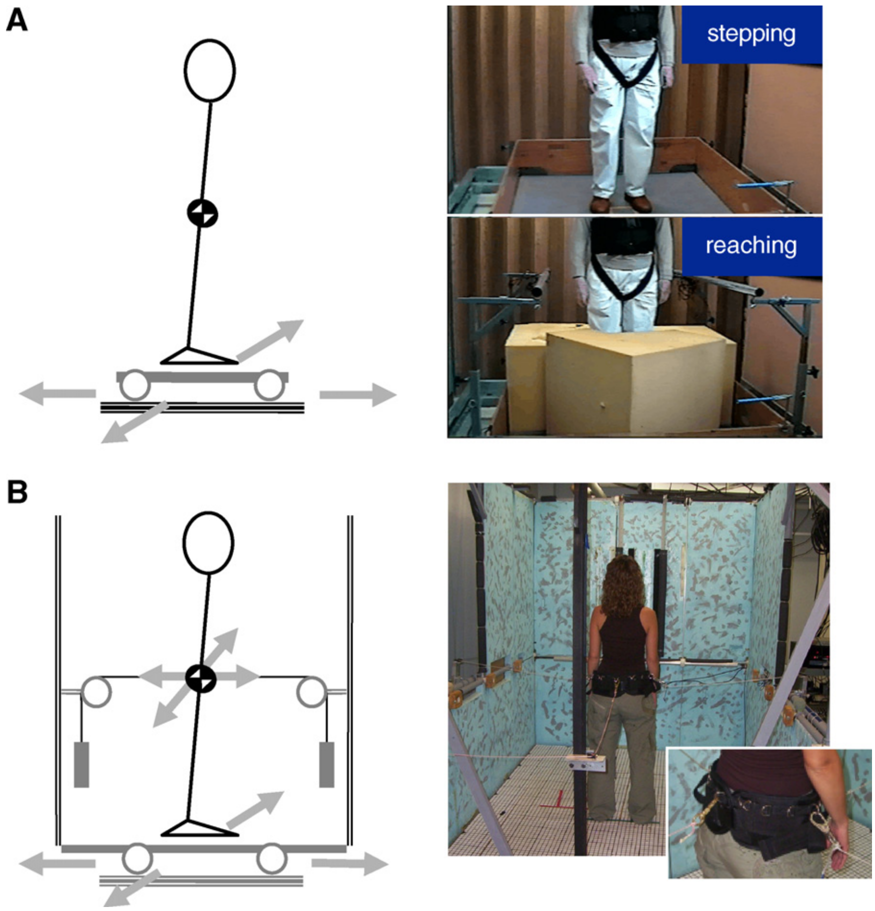

Fig. 1. Photographs and schematic drawings showing the equipment used to: (A) train improved control of change-in-support stepping and reaching reactions; and (B) assess the effects of the training. For both systems, subjects wear a safety harness anchored to the ceiling. Both systems can deliver perturbations unpredictably in forward, backward, left and right directions. The training platform (panel A) is driven by pneumatic cylinders, and the magnitude of the platform acceleration is varied (1–4 m/s^2) by adjusting the compressor air pressure. Handrails that are adjustable in height (87–101 cm) and position (37–42 cm from midline) can quickly be installed or removed. A customized pressure mat (1.2 m × 1.2 m; CIR Systems Inc., Havertown, PA) measures step placement and timing, force-sensing resistors on the handrails record reach-to-grasp timing, and a dual-axis accelerometer measures platform acceleration. The motor-driven motion platform and associated instrumentation used during the assessments (panel B) are described in more detail elsewhere (Maki et al., 1996, 2003). A custom-built waist-pull perturbation system is mounted on this platform, so that the nature of the perturbation (support-surface motion versus cable pull) can be varied unpredictably. The waist pulls are applied by dropping a weight attached to a belt worn around the pelvis via a cable and pulley system. Four separate cables are attached to the belt, so that the subject is pulled unpredictably forward, backward, left or right when the weight is dropped, depending on which cable is attached to the weight (Mansfield et al., 2007).

commonly lead to falls in daily life; hence, the adaptations that result from training with predictable perturbations may have limited generalizability.

As detailed previously (Mansfield et al., 2007), the training protocol was designed to include features known to promote motor learning: individualization, specificity, overload, adaptation-progression and variability (Briggs, 2001). To further promote optimal learning, feedback is gradually reduced as training progresses, instructions that pertain to the "whole response" (rather than specific motor sub-tasks) are given and an external focus (handrails or barriers) is provided wherever possible (Hodges and Franks, 2004; Vickers et al., 2004). Thus, for example, subjects are given no specific instructions about weight shifting or control of the limb trajectory. To counter the instability that leads to multiple-step reactions, they are simply told to take as few steps as possible. To reduce use of crossover steps that can lead to destabilizing inter-limb collisions, subjects are simply told to avoid contacting foam-rubber barriers placed in front of and behind the feet. To increase the speed of reaching reactions, subjects are instructed to grasp the rail as quickly as possible.

The training comprises three 30-min sessions per week, over six consecutive weeks. Stepping and reaching are trained separately during each session. To train reaching, handrails are installed and foot movement is restricted by foam-rubber barriers. After initially determining the minimum perturbation magnitude that evokes a CIS reaction, the magnitude is increased in subsequent sessions whenever the subject is able to recover equilibrium without difficulty by executing a single stepping or reaching reaction. Concurrent cognitive and movement tasks are included during later sessions so as to distract subjects from the balance task and provide a more realistic simulation of the demands of controlling balance in daily life. The variation in task conditions is intended to prepare subjects for a variety of balance-loss situations and thereby enhance the generalizability of the training effects.

2.3. Testing of the intervention

A pilot study was performed to evaluate the feasibility of implementing perturbation-based training in a clinical setting, and to evaluate the degree to which older adults with documented instability problems are willing and able to tolerate the training procedures. The study involved ten older adults who were referred to a clinical falls prevention program, due to problems with instability, falling and/or fear of falling. Subjects were assigned, at random, to either the perturbation-based program (PERT) or a program that focussed on training of rapid volitional stepping and reaching movements (VOL). Two of the initial ten subjects dropped out for reasons that were unrelated to the balance training; hence, eight subjects (four PERT, ages 79–89; four VOL, ages 69–86) completed the 6-week training program.

The pilot results support the feasibility and safety of the perturbation-based program, and provide no evidence that balance-impaired older adults would be less able or willing to tolerate this approach in comparison to training of volitional movement. Of the 18 prescribed training sessions, the average number of sessions attended was 14.5 (9–17) for the PERT group and 13.5 (12–18) for the VOL group. The average number of repetitions that each subject completed was 608 (335–774) for the PERT group and 738 (610–936) for the VOL group. All PERT subjects were able to progress to higher perturbation magnitudes over the course of the training (Fig. 2). No subjects indicated that they felt unsafe during the training, and there were no injuries or other adverse outcomes in either training program. Only three subjects (1 PERT, 2 VOL) reported that they found the training difficult. All but one subject felt that their performance improved with time, and four subjects (3 PERT, 1 VOL) felt that the training improved their ability to prevent themselves from falling.

A randomized controlled trial to evaluate the efficacy of the perturbation-based training program is in progress. The study involves community-dwelling older adults (age 64–80) who have reported a recent history of instability, falling or fall-related activity restriction, but are able to walk and stand without aid. Subjects are assigned to either the perturbation-based training or a control group, based on a stratified randomization that controls for gender and age and for baseline stepping and reaching performance (i.e. tendency to take multiple steps to recover balance and reach-to-grasp reaction time). The control group undergoes a program of flexibility and relaxation training that involves the same time commitment and degree of interaction with the experimenter as the perturbation-based program. Subjects undergo assessment of CIS reactions immediately before and after the training program, using a multi-directional waist-pull system that is mounted on a multi-directional motion platform (Fig. 1B). The timing, direction, magnitude and type of perturbation (waist pull or surface translation) are varied in an unpredictable manner, to deter predictive control of the response. The platform perturbations will indicate whether the training improved the targeted features of the CIS reactions, whereas the use of a distinctly different perturbation method (i.e. the waist pulls) will allow the generalizability of the training effects to be examined.

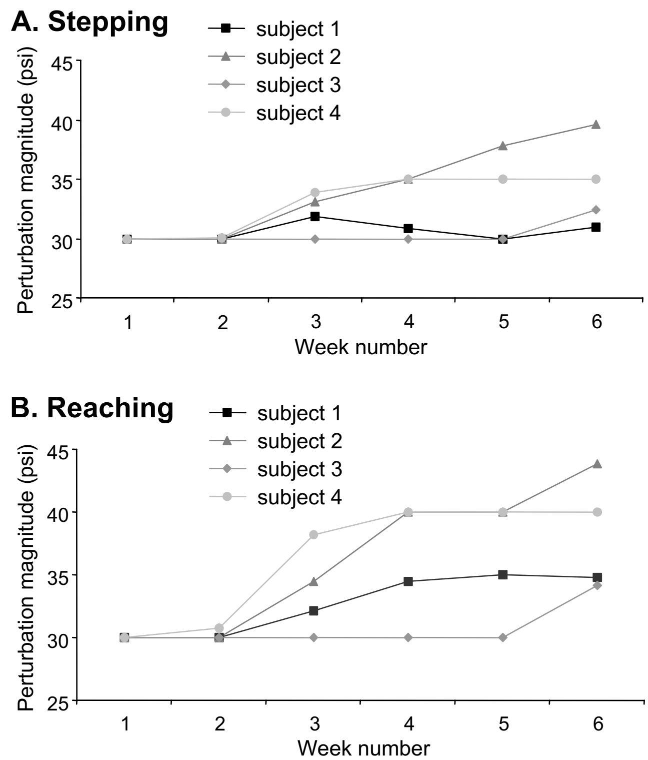

Fig. 2. Progression in perturbation magnitude over the course of the balance training program, in four pilot subjects, for: (A) step reactions; (B) reaching reactions. The perturbation magnitude was varied by adjusting the pressure of the air delivered to the pneumatic cylinders. For example, a pressure of 30 pounds per square inch (psi) resulted in peak platform accelerations of 1–1.7 m/s^2; 50 psi resulted in peak accelerations of 1.6–2 m/s^2.

3. Intervention #2: balance-enhancing footwear inserts

3.1. Background

Age-related reduction in cutaneous sensation is very common (Verrillo, 1993), and has been shown to predict an increased risk of falling (Lord et al., 1994). The cutaneous mechanoreceptors on the sole of the foot play an important role in controlling a number of specific aspects of balance (Watanabe and Okubo, 1981; Do et al., 1990; Priplata et al., 2003; Meyer et al., 2004), but appear to be particularly important in providing the CNS with information pertaining to the stability limits of the base-of-support and the state of contact between foot and ground (Maki et al., 1999; Perry et al., 2000, 2001), information that is crucial for the control of stepping reactions. This suggests that 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 water) (Perry et al., 2000). This 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 step termination. 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 attenuation 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 (Maki et al., 1999). The facilitation was accomplished by adhering flexible plastic tubing (3 mm in diameter) to the perimeter of the foot sole (Fig. 3A). By placing the tubing around the periphery, we ensured that the effect of 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 causes the tubing to indent the skin, thereby increasing stimulation of nearby cutaneous receptors. Older adults executed multiple-step reactions less frequently and backward excursion of the center-of-pressure decreased when the tubing was adhered to the foot sole.

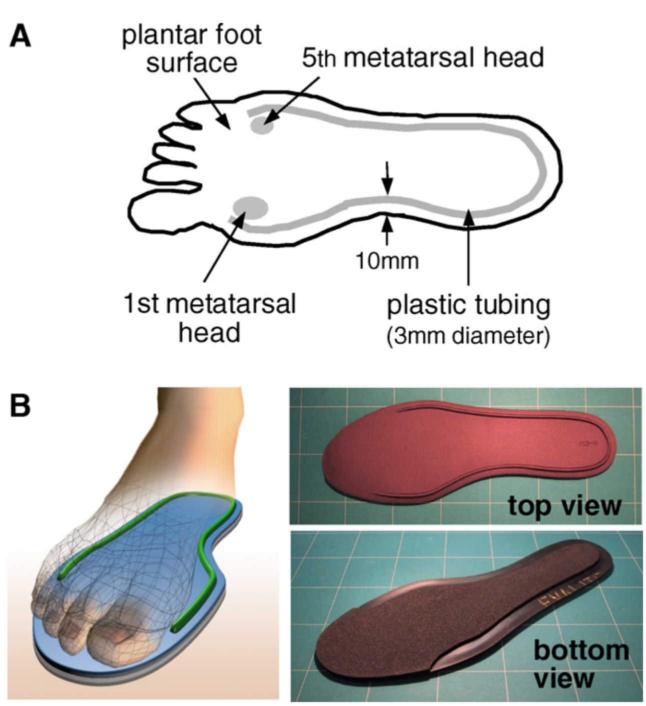

Fig. 3. Methods used to facilitate plantar cutaneous sensation: (A) set-up used in the initial experiments; (B) patented insole design (*SoleSensor*) developed on the basis of the experimental findings.

3.2. Description of the intervention

The intervention is a footwear insert, known as *SoleSensor* (www.hartmobility.com; US patent #6.237.256 issued May 29, 2001), which has a raised compliant ridge around the perimeter (Fig. 3B). 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.

3.3. Testing of the intervention

An initial clinical trial has been performed to determine whether the benefits of the insole persist over a prolonged period of daily use (12 weeks), 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.

The details of the clinical trial are provided elsewhere (Perry et al., 2006, submitted for publication). 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 weeks and 20 wore a conventional insole. A gait perturbation protocol (walking over uneven terrain) was used to assess dynamic balance control (i.e. excursion of the center-of-mass in relation to the base-of-support). These tests were performed initially at baseline and were then repeated after subjects wore the assigned insoles for 12 weeks. Participants also sent in weekly postcards with information pertaining to insole comfort, hours of wear and falls.

The gait perturbation assessments indicated that *SoleSensor* improved the ability to stabilize the body during gait, and that this benefit persisted after 12 weeks of wearing the insole (Fig. 4). Furthermore, nine subjects who wore conventional insoles experienced one or more falls over the 12-week period, whereas only five subjects fell while wearing the *SoleSensor*. Although there were initial reports of discomfort in ten cases, all subjects were able

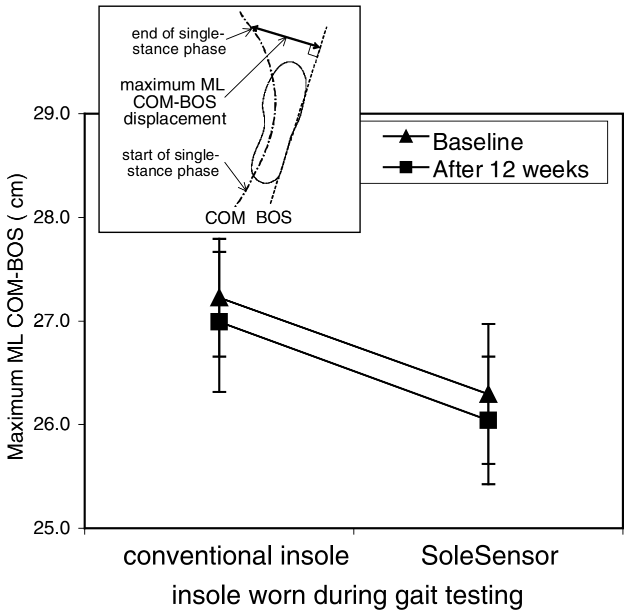

Fig. 4. Example result showing the influence of the *SoleSensor* facilitatory insole on medio-lateral (ML) displacement of the center-of-mass (COM) in relation to the lateral base-of-support (BOS) limits at the end of the single-stance phase, while walking on uneven terrain. Larger values indicate greater displacement of the COM toward the BOS limits about to be established by the landing of the contralateral foot. Means and standard deviations are shown for the 20 subjects who wore the *SoleSensor* insole for 12 weeks. Note that the effect of the *SoleSensor* insole (in comparison to the conventional insole) was the same in both testing sessions, i.e. before and after the 12-week period.

to tolerate the *SoleSensor*, and most (17 of 20) indicated that they would like to continue wearing the insole on a long-term basis.

4. Intervention #3: safer walking aids

4.1. Background

Mobility aids, such as walkers, are often prescribed to help older individuals maintain balance while performing activities of daily living; however, some studies suggest that use of conventional aids may actually increase risk of falling in some situations (Wright and Kemp, 1992; Charron et al., 1995; Bateni et al., 2004a; Bateni and Maki, 2005). One possible problem pertains to the potential for walkers to interfere with, or constrain, lateral movement of the legs and thereby impair the capacity to step laterally to recover from a loss of balance. Although walkers can help to enhance postural stability (by increasing the effective base-of-support and allowing stabilizing hand-reaction forces to be generated), this may be insufficient to recover equilibrium in some situations (e.g. if the postural perturbation is large or the user is unable to generate sufficient stabilizing hand-reaction force). In such situations, it may be necessary to execute a stepping reaction in order to recover equilibrium.

In an initial study, we used lateral platform perturbations to study the effect of a standard pickup walker on ability to recover balance by stepping laterally, in 10 healthy young adults (Bateni et al., 2004a). The results indicated that collisions between the swing foot and walker were very common (60% of trials), and led to a significant reduction (26–37%) in lateral step length (compared to no-collision trials). Typically, the tendency to push on the walker in an effort to recover equilibrium prevented subjects from lifting and moving the aid, either to avoid collision or to re-establish a more stable base-of-support. This initial study involved perturbation of bipedal stance. In a second study involving the same subjects, we assessed the effect of the walker on ability to respond to lateral perturbation during gait (Cheng et al., submitted for publication-a). Although collisions between the swing foot and walker were not as frequent as in the stance-perturbation study, such collisions did occur in a substantial proportion of trials, and were most common when the perturbation caused the subject to fall laterally toward the lifted foot (collisions in 36% of trials). Despite the high frequency of foot/device collisions, the young adults tested in these two studies were almost always able to recover equilibrium; however, it seems likely that aging could lead to greater difficulty in coping with the consequences of the collisions, as well as increased frequency of collisions.

4.2. Description of the intervention

The intervention involved modifying the design of the standard pickup walker to allow more space for unimpeded lateral foot movement and thereby enhance ability to step laterally to recover balance. At the same time, we were cognizant of the need to avoid design changes that could compromise mobility and maneuverability. For this reason, we avoided increasing the width of the walker, which could interfere with ability to move through doorways or narrow hallways. We also avoided changes that would substantially increase the weight or inertia, which could lead to fatigue and reduced ability to use the walker. Two simple design modifications were made: (1) the horizontal bars connecting the front and rear walker posts near the base of the walker were replaced with arch-shaped struts; (2) the distance between the front and rear walker posts was increased by 20 cm, so that the rear walker posts were no longer adjacent to the subject's feet (Fig. 5).

4.3. Testing of the intervention

The new walker designs were tested using a platform-perturbation protocol similar to that used in our earlier work (Bateni et al., 2004a). We elected to focus, in this initial study, on perturbation of bipedal stance, since foot/device collisions occur most frequently in this situation. Six healthy young adults were each tested with a conventional pickup walker, the "arched walker" and the "extended arched walker" (Fig. 5A–C, respectively), and also performed trials in which no mobility aid was used (Cheng et al., submitted for publication-b).

Fig. 5. Photographs of a standard pickup walker (A) and the walker designs that were modified to reduce restrictions on lateral stepping reactions. The overlaid line drawings highlight the arched strut that replaces the lower horizontal bar (B) and the extension of the walker length that serves to move the rear posts away from the feet (C).

Results showed a significant reduction in the frequency of foot/device collisions when using the extended arched walker, in comparison to the standard walker (5% of trials versus 31%), whereas the arched walker yielded an intermediate level of improvement (collisions in 14% of trials). As in the earlier young adult studies, however, there was no clear relation between the reduction in collision rate and any measurable improvement in stability. Further study involving older adults and a wider variety of task conditions (including perturbation of gait) is needed to establish whether the new designs actually do increase stability in seniors.

5. Intervention #4: handrail cueing systems

5.1. 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 (Ghafouri et al., 2004; Zettel et al., 2005). 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 (Salthouse, 1992; Munoz et al., 1998; Kemps and Newson, 2006). In addition, aging may impair ability to disengage attention from an ongoing motor or cognitive task (McDowd, 1997). Although no studies have yet directly examined effects on control of CIS 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 (Owsley et al., 1998). A recent study has also shown that decrease in UFOV is correlated with reduced mobility in older adults (Owsley and McGwin, 2004).

5.2. Description of the intervention

The intervention is a cueing system (patent pending) that is designed to automatically and involuntarily draw attention to a handrail as the person approaches. 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 that might otherwise have caused the presence of the handrail to pass undetected.

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 (Posner and Cohen, 1984). 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 (Hommel et al., 2001). 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 begin flashing as the individual approaches the handrail, thereby providing an abrupt onset cue. In order to enhance visibility and improve object recognition, the railing itself is black. This provides high contrast with respect to both the LEDs and typical backgrounds (e.g. white walls). In pilot tests (16 subjects) performed to compare the green and yellow LEDs, subjects tended to prefer the green LEDs, perceived them to be brighter and were more likely to think that they encouraged use of the rail; therefore, we elected to use green LEDs in the main study.

A second version of the cueing system incorporates a concurrent verbal prompt (e.g. "attention – use the handrail") that is also triggered by the proximity sensor and delivered by speakers built into the handrail mounting fixtures. The combination of visual and auditory cues is expected to enhance attention capture, in view of evidence that congruent multi-modal stimuli are more effective in influencing behavior in comparison to stimuli that involve a single sensory modality, particularly so in older adults (Laurienti et al., 2006).

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 people to hold the rail 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. Rather, the influence of the cueing on the control of subsequent CIS reactions is expected to be a much more consistent and robust benefit. By capturing attention, even momentarily, the cueing may help to incorporate the rail into the individual's "spatial map" and thereby facilitate rapid grasping of the rail in response to an unexpected loss of balance. More details

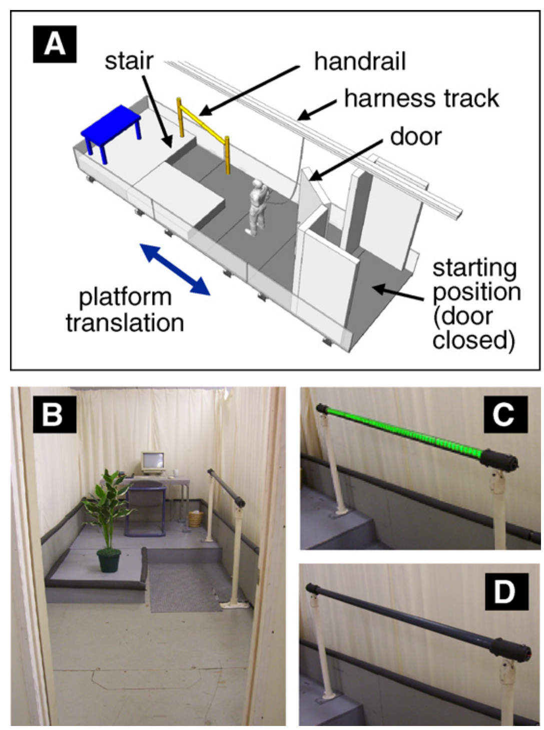

Fig. 6. Schematic drawing (A) and photograph (B) of the large (2 m × 6 m) motion platform used to study the handrail cueing systems (C and D). (B) shows a view (through the doorway) of objects mounted on the platform so as to simulate the visual complexity of a typical "real-life" living environment; 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. The platform is triggered by a pressure mat to suddenly and unexpectedly move forward as the subject approaches the handrail, so as to evoke a reaching reaction. The handrail cueing is triggered by a photocell to begin ~2 s before the subject comes to the rail; during visual cueing, green LEDs mounted within the translucent rail are controlled to flash on (C) and off (D).

about the cueing systems are provided elsewhere (Scovil et al., in press).

5.3. Testing of the intervention

Preliminary testing of the handrail cueing systems is in progress (Maki et al., 2006). The protocol involves the use of an extended (2 m × 6 m) motion platform configured to simulate a realistic living environment, including a stair, a handrail and various visual distracters (Fig. 6). The platform is triggered to move suddenly as the subject approaches the handrail, and a deception is used to ensure that the perturbation is truly unexpected. To prevent learning and adaptation, subjects perform only one trial, which is their very first exposure to the perturbation and environment. Three handrail conditions are tested: (1) visual cue, (2) combined visual and verbal cues, and (3) no cueing (conventional handrail). In the main study, older adults (aged 64–75) will be assigned to one of these three conditions using a randomization procedure that controls for gender, age, fear of falling and other variables that could potentially confound the results. The effects of the cueing systems are assessed by recording gaze behavior (e.g. timing and duration of gaze shifts toward the rail, visual angle between the point of gaze and the rail) and features of the handrail use and reaching reactions (e.g. frequency of rail use, timing of rail contact, type of grip, efficacy in preventing a fall against a safety harness).

6. Discussion

The four interventions described here represent quite diverse, yet complementary, approaches to reducing fall risk by improving the control of CIS balance reactions. To our knowledge, no other fall-prevention approaches have targeted a specific type of balance-recovery reaction in this way. We propose that it is crucial to target CIS 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.

To facilitate widespread "knowledge transfer", fall-prevention interventions need to be simple and inexpensive. This is certainly the case for the *SoleSensor* insole, as well as the safer walker designs. In each case, a relatively simple design modification is all that is required. The use of vibrating insoles to facilitate plantar cutaneous sensation (via the phenomenon of stochastic resonance) has recently received much attention in both scientific and public forums (Priplata et al., 2003); however, such insoles require a power supply, electronic circuitry and electromechanical transducers. In contrast, the *SoleSensor* is a totally passive insole that will be much less expensive to manufacture and use. Ultimately, a clinical trial to compare the efficacy of the two approaches would be a valuable contribution.

The proposed walker design changes are also relatively simple and inexpensive. Further research is needed to establish the functional benefits of the design changes for older adults. Nonetheless, given the potential advantages in reducing risk of falling and the lack of any significant disadvantages, it would seem prudent for walker manufacturers to eliminate lateral connecting bars that can impede lateral stepping movements (instead using arch-shaped struts, as in Fig. 5B, or other design changes to maintain the structural integrity of the walker). This is particularly important in view of the evidence that walker-related falls can result in very serious and even fatal injury (Charron et al., 1995).

For the balance-training program, the main obstacle that might impede widespread transfer to clinical practice is the need for a safe and well-controlled perturbation-delivery system (Maki and McIlroy, 2005). We elected to use platform translation in our study, as a safe and convenient method of delivering well-controlled multi-directional perturbations. The pneumatic platform that we developed for this study could likely be sold for less than currently available motion platforms (typically costing >US $25,000), but may still be too expensive for widespread clinical use. Although less expensive methods such as manual perturbation (Jöbges et al., 2004) may ultimately prove to be feasible, we felt that it was important to have more precise control over the perturbation features, in this initial study, in order to maximize the efficacy of the perturbation-based training approach. Once the efficacy of the approach has been established, less expensive perturbation methods will be evaluated.

The handrail cueing system is the newest of the interventions and is not yet ready for knowledge transfer. There is a need to complete our ongoing studies to determine whether the cueing is actually beneficial, and to ensure that there are no negative effects (e.g. whether the flashing lights might actually deter some people from using the handrail).

In concluding, it is worth noting that all four of the intervention approaches described here have the potential to counter lateral instability, and the associated risk of sustaining debilitating and life-threatening hip–fracture injuries (Hayes et al., 1996). The walker modifications specifically target lateral stepping reactions, while components of the balance training program address both lateral stepping reactions and control of lateral stability during forward and backward steps. In addition, the *SoleSensor* insoles may enhance ability to control lateral stability during the landing phase of forward steps. Finally, the handrail cueing system, as well as the reaching component of the balance-training program, may facilitate more effective use of reach-to-grasp reactions to compensate for impaired control of lateral stability.

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