Title: Reducing fall risk by improving balance control: Development, evaluation and knowledge-translation of new approaches

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Keywords: balance training, falls prevention, footwear, handrails, mobility aids

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Published in final edited form as:
J Safety Res. 2011 December; 42(6): 473–485. doi:10.1016/j.jsr.2011.02.002.

Abstract

Problem: Falling is a leading cause of serious injury, loss of independence and nursing-home admission in older adults. Impaired balance control is a major contributing factor.

Methods: Our research is directed at determining specific aspects of balance that need to be targeted and applying this information in the development of new cost-effective interventions and assessment tools. Initiatives to facilitate knowledge-translation of this work include setting up a new network of balance clinics, a research-user network and a research-user advisory board.

Results: New balance assessment and training methods; mobility aids and neuro-prostheses; footwear and garments; handrail, grab-bar and safety-pole systems.

Impact on Knowledge Users: A new balance-assessment tool has been implemented in the first new balance clinic, a new balance-enhancing insole is available through pharmacies and other commercial outlets, and handrail design recommendations have been incorporated into ten Canadian and American building codes. Work in progress is expected to have further impact.

Introduction

The ability to ambulate and move about safely, without falling, is a fundamental aspect of mobility, yet falling is a very common occurrence in older adults and is a leading cause of serious injury, loss of independence and nursing-home admission (Sattin et al., 1990; Tinetti & Williams, 1997). In addition, fear of falling can lead to social withdrawal and inactivity (Arfken et al., 1994; Murphy & Isaacs, 1982; Tinetti et al., 1994). Although the causes of falls are varied and complex, impaired control of gait and balance is widely recognized to be a major contributing factor [for reviews, see (Maki & McIlroy, 1996; Maki & McIlroy, 2003; Maki & McIlroy, 2005)]. Consequently, interventions to improve control of balance during gait and other activities are likely to have a significant impact on risk of falling.

Although many aspects of balance and gait can influence risk of falling, a critical factor is the ability to respond effectively to balance perturbations. These perturbations can arise from: 1) slips, trips and missteps; 2) collisions or other physical interactions with objects (animate or inanimate) in the environment; or 3) the destabilizing effects of volitional movement (Maki & McIlroy, 2003). Recovery of equilibrium involves regulating the relationship between the center-of-mass of the body and the base-of-support (Pai & 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 & McIlroy, 1997; Maki & McIlroy, 1999). These “change-in-support” (CIS) 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 are also prevalent even when the perturbation is relatively small (Maki & McIlroy, 1997; Rogers et al., 1996).

The purpose of this paper is to describe our ongoing efforts, and progress to date, in promoting safe mobility and reducing risk of falling in older adults. This work includes research to determine specific aspects of balance that need to be targeted and application of this information in the development of new cost-effective assessment tools and interventions to identify and counter age-related deficits in balance control. In accordance with theoretical frameworks for increasing knowledge use and moving knowledge into action (Graham et al., 2006), our work also encompasses a number of knowledge-translation strategies to facilitate and promote uptake of these new approaches into routine health-care practice. The emphasis of many of the new approaches is on improving the capacity to execute rapid and effective CIS reactions, for reasons outlined above. The focus is on research and development performed in Toronto (Canada), in two primary locations: the Centre for Studies in Aging (Sunnybrook Health Sciences Centre) and the Toronto Rehabilitation Institute. The researchers are members of a team funded by the Canadian Institutes of Health Research, with the mandate to develop “Innovative Approaches to Optimize Balance and Gait in Older Adults”.

Development of new interventions to reduce fall risk

Footwear and garments

Age-related reduction in cutaneous sensation is very common (Perry, 2006; Verrillo, 1993), and appears to impede effective stepping reactions in some specific ways (Maki et al., 1999; Perry et al., 2000; Perry et al., 2001). In an effort to counter these problems, we investigated a very simple approach to facilitate cutaneous sensation (Maki et al., 1999). This involved creating a “ridge” by adhering flexible plastic tubing (3mm diameter) to the perimeter

of the foot sole (Figure 1a). 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. The increased stimulation is intended to compensate for age-related insensitivity due to loss of cutaneous receptors, morphologic changes in the receptors and/or changes in the elastic properties of the skin. Results showed that the facilitation was effective: 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. The outcome of this work was a new type of a footwear insert, known as *SoleSensor*® (U.S. patent issued in 2001, licensed to Hart Mobility, Inc.), which has a raised compliant ridge around the perimeter (Figure 1b). 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.

< insert Figure 1 about here >

In a subsequent clinical trial (Perry et al., 2008), we tested 40 community-dwelling older adults (aged 65-75 years) 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 the effect of the insole on lateral stability, at baseline and after wearing it for 12 weeks. These tests indicated that *SoleSensor* significantly improved the ability to stabilize the body during gait, and that this benefit persisted after 12 weeks of wearing the insole. 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 but one subject tolerated the *SoleSensor*, and most (17 of 20) indicated that they would like to continue wearing it on a long-term basis. This simple change in insole design thus appears to be a viable intervention to counter age-related balance deficits, and a subsequent study has indicated that it also improves gait stability in persons suffering from Parkinson's disease (Jenkins et al., 2009). Other related ongoing work by team members is examining effects of other aspects of footwear design on balance control (Menant et al., 2008; Perry et al., 2007).

A second ongoing initiative is aimed at improving the ability of older adults to remain active in the winter without jeopardizing safety. Previous research has established that cold weather can lead to impaired physiological function in seniors, as well as increased morbidity, mortality, risk of falling, immobility and social isolation (Keatinge, 2002; Mercer, 2003; Nayha, 2002). To better understand these problems and the specific factors that contribute to increased fall risk and immobility, we performed an initial study in which we used qualitative research methods (interviews, surveys, focus groups) with 40 older-adult volunteers to elucidate the specific mobility-related concerns and problems faced by older adults during the winter (Row et al., 2005a; Row et al., 2005b; Row et al., 2005c). This work has helped us to identify priorities for the next stage of this research, which will address how best to design footwear, anti-slip devices and clothing (as well as mobility aids) to facilitate safe mobility during slippery conditions and cold weather.

Handrails, grab-bars and safety poles

Handrails (as well as grab bars and safety poles) can be designed to promote more effective reach-to-grasp reactions, by maximizing ability to: 1) grasp the rail rapidly and effectively, and 2) generate stabilizing reaction forces and moments once the rail has been grasped (Maki et al., 2006). Our earliest studies, which focussed on the latter issue, involved a total of 42 young and 43 older adults, and assessed the effect of the handrail design on ability to generate stabilizing forces and moments when pushing and pulling on the rail at various stair pitches (Maki, 1985; Maki et al., 1984; Maki et al., 1985). Results indicated that the handrail should be considerably higher (94cm) than many existing building standards, so as to increase the moment arm of the rail reaction-force relative to the feet. A circular shape (38mm diameter) enabled a “power grip” and allowed large forces to be generated; rails that forced a “pinch grip” were less effective. Enamel and varnish surfaces were more effective than chrome-plated and acrylic surfaces in allowing the hand to generate force without slipping. See Figure 2a.

< insert Figure 2 about here >

Related work has involved the development of: 1) a safety-pole system (*SturdyGrip*TM) that has a contoured surface to promote effective grasping and can be easily installed (without tools) wherever needed (Figure 2b), and 2) a novel stairway handrail (*LifeRail*) which is positioned and shaped so it can be “hugged” under the arm (Figure 2c). The latter has the advantage of increasing the effective height of the rail, so that a larger stabilizing moment can be generated. In addition, large stabilizing reaction forces can be generated by hugging the rail, even in persons with poor hand strength. Pilot tests have provided evidence to support the biomechanical advantages of the *LifeRail* design; however, these tests have also raised concerns that some individuals may use the rail inappropriately, i.e. by attempting to grasp the top surface, which was not designed to permit effective grasping (Figure 2c.3). To counter this problem, alternative designs are being studied, for example, a simple double-rail design (Figure 2c.5). This still allows the rail to be hugged under the arm, as per the *LifeRail* concept, but also permits either rail to be grasped effectively with the hand (Gorski, 2005). This design has the further advantage that it is simpler and less expensive than the *LifeRail* and thus has greater potential for widespread use.

More recently, we have begun to use a motion-platform balance-perturbation system to investigate the effect of handrail design on ability to reach and grasp the rail dynamically, during a simulated stairway loss of balance (Maki et al., 1998). It was unclear, prior to this study, whether it is even possible to grasp the rail and generate stabilizing force fast enough to prevent a stair fall. Initial tests (4 young adults) indicated that the hand can, in fact, reach the rail and generate large force (up to 60% of body weight) very rapidly (<1sec). Surprisingly, a large pull-up force was generated, which required the fingers to be wrapped around the rail undersurface (i.e. a power grip). The hand typically attacked the rail with fingers fully extended, which implies a need for substantial wall clearance. Although the angle of attack varied widely (depending on subject-to-rail distance), a circular shape always allowed a power grip to be achieved.

In order to reach to grasp a handrail for support, the central nervous system (CNS) requires visuospatial information about the location of the rail; however, it appears that aging may impair ability to “notice” objects such as handrails when moving about in an unfamiliar environment (King et al., 2009), which may in turn impair the ability to rapidly grasp the rail in the event that a sudden unexpected loss of balance occurs. One approach to counter this problem is to use cueing systems to automatically and involuntarily draw attention to a handrail as the

person approaches. In an initial study involving 24 young adults (Corbeil et al., 2005), we explored passive color cueing, i.e. the effect of using a bright yellow rail, but the results were inconclusive. In comparison to a gray rail, the yellow rail was associated with an increased tendency to look at the rail upon entering a new environment and an earlier opening of the hand aperture in response to a subsequent balance perturbation, yet there was no obvious relationship between these trends and the ability to grasp the rail successfully. Although it is not yet clear whether a yellow rail will promote “attention capture”, bright colors and high contrast will, at the very least, have the benefit of making the rail more visible, which may be particularly important for older persons with visual deficits.

In subsequent studies, we have focused on developing an active handrail cueing system (patent pending) in which a visual cue (flashing lights) and/or auditory cue (a verbal prompt to use the handrail) are activated by a photoelectric proximity-sensor as the individual approaches the handrail (Scovil et al., 2007a; Scovil et al., 2007b). The rail is a translucent black plastic tube and the lights (green or yellow light-emitting diodes) are mounted internally along the axis of the rail. The verbal prompt is issued by miniature speakers mounted in the rail or the mounting fixtures. The cueing is intended to help ensure that the presence and location of the rail is registered by the CNS during the approach to the rail. This, in turn, is intended primarily to facilitate rapid and effective grasping of the rail in response to an unexpected loss of balance, but may also increase the likelihood that persons will hold the rail “proactively” (before loss of balance can occur). In a large-scale study (120 older adults), we are comparing effects of multi-modal cueing (verbal+visual) and unimodal (visual) cueing to trials where no cueing is used (Maki et al., 2006; Maki et al., 2008c). Preliminary analyses, based on the first 54 subjects, indicate that subjects were more likely to look at the handrail and to hold the rail “proactively”, and were less likely to make grasping errors when reaching for the rail in reaction to an unexpected balance perturbation, in the multi-modal-cueing trials (McKay et al., 2008b). These preliminary results thus support the viability of handrail cueing as an intervention to reduce risk of falling; however, larger numbers of subjects must be analyzed to verify the initial trends in the data.

Mobility aids

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 (Bateni et al., 2004a; Bateni & Maki, 2005; Charron et al., 1995; Stevens et al., 2009; Wright & Kemp, 1992). 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 initial studies involving healthy young adults (Bateni et al., 2004a; Cheng et al., 2008), collisions between the step foot and walker were a remarkably common occurrence during step reactions evoked by lateral perturbation. Despite the high frequency of foot/device collisions, the young adults tested in these 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. To counter this

problem, we made some simple modifications to the design of the standard pickup walker, in order to allow more space for unimpeded lateral foot movement and thereby enhance ability to step laterally to recover balance (Cheng et al., 2008; Maki et al., 2008b). 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 narrow doorways or corridors. The design modifications involved: 1) replacing the horizontal bars connecting the front and rear walker posts (near the base of the walker) with arch-shaped struts; and 2) increasing the distance between the front and rear walker posts (by 20cm), so that the rear walker posts were no longer adjacent to the subject's feet (Figure 3). Testing in six healthy young adults (Cheng et al., 2008; Maki et al., 2008b) demonstrated that these two design changes greatly reduced the frequency of foot/device collisions (from 31% of trials to 5%). 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 who are dependent on walkers are needed to establish whether the new designs actually do increase stability in seniors, without causing any adverse effects.

< insert Figure 3 about here >

In related work, we recently developed a rolling walker ("rollator") that is instrumented with force and motion sensors and miniature video cameras in order to study the problems that occur when using walkers in "real-life" situations and environments (Tung et al., 2008). We anticipate that this approach will be valuable in identifying other walker design features that can lead to reduced stability or mobility, and in testing new designs to counter these problems. In addition to the walker studies, we demonstrated that the act of holding an object such as a cane can inhibit the natural tendency to reach and grasp a more stable object (e.g. a handrail) for support (Bateni et al., 2004b). This line of research is expected to result in guidelines for safer use of mobility aids. We also plan to investigate whether a handrail cueing system can be effective in prompting the person to use the rail, rather than relying on a mobility aid.

Neuro-prostheses

Functional Electrical Stimulation (FES) systems, which use surface electrodes to activate leg muscles, have been used to improve walking (Popovic et al., 2001a; Quintern, 1998; Thrasher et al., 2006) and standing (Bajd et al., 1999; Davis et al., 1999; Hunt et al., 1998; Kralj et al., 1993; Riener & Fuhr, 1998; Veltink & Donaldson, 1998) in persons with spinal-cord injury (SCI). However, in these applications, balance was maintained by holding on to a walker or a standing frame. Our goal has been to develop an FES system that can provide automatic arms-free balance control in persons with SCI, and to extend the application of such a system to counter age-related balance impairments (i.e. in the absence of SCI). Ultimately, we aim to design FES systems that can assist in stabilization during locomotion and enhance CIS balance-recovery reactions; however, the initial goal is to enhance arms-free standing balance.

In work to date, we have carried out a series of theoretical analyses and experiments to investigate the mechanisms of balance control during quiet standing in able-bodied subjects (Kim et al., 2007; Kim et al., 2006; Masani et al., 2006; Vette et al., 2007). This work has challenged prevailing models involving feedforward control mechanisms, and has established that a feedback control system is a viable method for regulating standing balance. Using this type of controller, we then developed a prototype FES neuro-prosthesis and tested it with a subject who was unable to stand as a result of a spinal-cord injury (Vette et al., 2007). When using the FES

neuro-prosthesis, this subject was able to stand without assistance, and demonstrated regulation of postural sway that was similar to able-bodied subjects.

In addition to the above work, we have completed experiments to develop a quantitative criterion to characterize level of stability during quiet standing (Masani et al., 2007; Tortolero et al., 2007). Our intention is to use this criterion to design a portable sensor for measuring balance, which will then be integrated with the FES neuro-prosthesis to regulate stiffness of the leg and lower-back joints in real-time, according to the person's state of stability. This sensor could also be used to train older adults how to identify moments when they are marginally stable during standing and how to avoid these events and maintain stability. The integrated FES and sensor system will act as an intelligent stabilizing orthosis that could be used, either as an assistive device or training tool, to enhance ability of older adults to maintain balance during activities of daily living without stepping or reaching for support. Avoidance of unnecessary stepping or reaching reactions would be of benefit to persons who are prone to experiencing problems during the execution of these reactions (Maki & McIlroy, 2005). Furthermore, the ability to achieve stable stance, in itself, can provide functional and physiological benefits for persons who are otherwise unable to stand safely (Vette et al., 2009).

Balance training

Evidence that the neural control of volitional and perturbation-evoked limb movements differs in some fundamental ways (Gage et al., 2007; Maki & McIlroy, 1997; Maki & McIlroy, 2005) suggests that the most effective approaches to train CIS stepping and grasping reactions will involve use of balance perturbations. Perturbation-based training of CIS reactions has, in fact, recently begun to receive attention (Jöbges et al., 2004; Maki & McIlroy, 1999; Maki & McIlroy, 2005; Maki & McIlroy, 2006; Protas et al., 2005; Rogers et al., 2003; Shimada et al., 2004). Four initial studies 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 step reaction time in older adults (Rogers et al., 2003; Shimada et al., 2004), but did not assess effects of the training on compensatory stepping.

We have recently completed pilot testing, as well as an initial randomized controlled trial (RCT), of a new perturbation-based balance-training program designed to counter impairments in four specific features of CIS reactions that are associated with increased fall risk: 1) slowing of reaching reactions; 2) the need to take multiple steps to recover equilibrium; 3) impaired control of lateral stability during forward and backward step reactions; and 4) impaired control of limb movement (i.e. limb collisions) during lateral step reactions (Maki et al., 2008b; Mansfield et al., 2007). During the training (three 30-minute sessions per week, for six weeks), sudden unpredictable platform motions (Figure 4a) were administered in a highly unpredictable manner, so as to prevent subjects from learning to use predictive control strategies that are unlikely to be helpful in responding to the unpredictable perturbations that commonly lead to falls in daily life. Other aspects of the training program (e.g. instructions, feedback, individualized progression in perturbation magnitude) were designed to promote optimal motor learning. To simulate the demands of controlling balance in daily life, a variety of concurrent cognitive and movement tasks were introduced during the later training sessions.

< insert Figure 4 about here >

The initial pilot study, which involved eight seniors who were referred to a Falls Clinic, supported the feasibility and safety of the perturbation-based program, and provided no evidence that balance-impaired older adults would be less able or willing to tolerate this approach in

comparison to training of volitional limb movement (Maki et al., 2008b). The results of the RCT (30 balance-impaired seniors, aged 64-80) demonstrated that the perturbation-based training was effective in improving three of the four targeted motor behaviors (Mansfield et al., 2010). Compared to a control group (flexibility and relaxation training), the perturbation-trained subjects showed greater reductions in multi-step reactions and limb collisions, in platform perturbation trials. There was also one effect that generalized to a distinctly different perturbation method (waist pulls): perturbation-trained subjects showed greater improvement in the speed of their grasping reactions, in comparison to the controls. These results support the viability of the perturbation-based training program; however, further work is needed to determine whether a maintenance program is required to retain the training benefits and to assess whether these benefits reduce fall risk in daily life.

Another approach to counter the adverse effects of aging on the ability to execute rapid and effective CIS reactions involves the use of computer-based training programs to improve relevant aspects of visual processing. Potential targets of the training program include overt visual attention (central vision), covert visual attention (peripheral vision), working spatial memory and gaze control. We have elected to focus on covert attention in our initial training study because of evidence that: 1) peripheral vision can play an important role in guiding reach-to-grasp reactions (King et al., 2010; King et al., 2009; Maki et al., 2008c); 2) older adults have a reduced ability to rapidly extract information from the peripheral visual field (as indicated by a reduction in the “Useful Field of View”, or UFOV) (Ball et al., 1988); and 3) a cost-effective computer-based “visual training” program can improve the UFOV in older adults (Ball & Sekuler, 1986; Ball et al., 1988) and can lead to lasting improvements in motor performance [e.g. driving (Roenker et al., 2003), as well as ability to rapidly perform instrumental activities of daily living (Edwards et al., 2002)]. While previous UFOV studies have focussed largely on driving performance, it can be argued that ambulation presents analogous demands for visual monitoring of one’s surroundings. In support of this, a recent study showed that poorer UFOV scores correlate with reduced mobility in seniors (Owsley & McGwin, 2004).

In our initial study, currently in progress, we are evaluating the effect of the computer-based UFOV training program (two one-hour sessions per week, for five weeks) on the ability to use peripheral vision to successfully execute rapid reach-to-grasp balance-recovery reactions (McKay et al., 2008a). The UFOV-training group is being compared to a “placebo” control group that performs a computer-based cognitive task (word puzzles) that does not involve visuospatial processing or peripheral vision. The study also includes a new “visual training” program based on video-game technology. Recent studies show that playing “first-person shooter” (FPS) video games can lead to dramatic and lasting improvements in spatial attention and speed of processing in young adults (Castel et al., 2005; Green & Bavelier, 2003; Green & Bavelier, 2007). Furthermore, typical video games have a built-in capacity for promoting both motor learning (requiring a progression through increasing levels of difficulty) and compliance (due to high levels of enjoyment, as well as the “addictive” properties of gaming). We therefore expect that this approach will be equally, if not more, effective than the UFOV in improving balance reactions, and will be more enjoyable for participants and better suited to be self-administered in the home, thereby increasing compliance and cost-effectiveness. We are using an FPS game that involves comical cartoon-like targets, based on pilot results that indicated that older adults were much more likely to enjoy playing this type of video game, in comparison to the realistic and violent FPS games tested in the previous young-adult studies (McKay & Maki, 2010).

Knowledge translation strategies and impact on knowledge users

Knowledge translation (KT) is a term used to describe the process of putting knowledge into action (Straus et al., 2009a), the purpose of which is to address the gap between what is known from research and implementation of this knowledge in practical forms by key stakeholders with the intention of improving health outcomes (Graham et al., 2006). The strategies that we are using to promote knowledge translation of our research findings and outcomes follow the “Knowledge to Action” process and involve both “end of grant KT” (matching findings from completed research activity to the needs of knowledge users) and “integrated KT” (involving stakeholders in ongoing research activity) (Graham et al., 2006).

Knowledge dissemination strategies

Although dissemination alone is not necessarily sufficient to ensure actual use of new knowledge, it is an important component of any KT plan and can be effective if appropriately-customized messages reach the intended target audience (Straus et al., 2009b). Accordingly, it is important to present the knowledge in formats and forums that are appropriate for the different types of decision-makers, and to avoid a “one-size-fits-all” journal publication approach (Lomas, 2009). We endeavor to meet these objectives by synthesizing our research outcomes with the existing literature in review articles that are tailored to the interests of specific research-user audiences, such as geriatricians (Maki & McIlroy, 1996), physical therapists (Maki & McIlroy, 1997; Maki & McIlroy, 1999), occupational therapists (Bateni & Maki, 2005), otolaryngologists (Maki & McIlroy, 2003), neurologists (Maki & McIlroy, 2005), ergonomists (Maki et al., 2008c) and podiatrists (Perry et al., 2009). In addition, we present our findings in professional magazines [e.g. (Ferne & Maki, 1999; Gage, 2005; Maki, 2000; Maki et al., 2003; Popovic et al., 2001b)], at falls-prevention workshops [e.g. (Maki, 2003; Maki, 2007)] and through interviews with the lay media and articles in the popular press. We have also contributed to the development of Best Practices Guidelines for fall prevention [eg (Registered Nurses Association of Ontario, 2005)].

A key component of our knowledge-dissemination strategy has been the establishment of a large network of research-users, the Falls & Mobility Network. This network is an unfunded alliance of researchers, research users and other key stakeholders with an interest in falls prevention, including seniors’ groups, health-care providers, hospital administrators, educators, and medical manufacturers and retailers. The network currently has 640 members, representing 192 institutions and companies. Knowledge exchange is promoted via a website (<http://sunnybrook.ca/research/?page=FallsMobilityNetworkHome>), email discussion groups and an annual one-day meeting.

Involving research users at an early stage

It is vitally important to get research users involved during all phases of the research process (Lomas, 2009), to ensure that the knowledge and technologies that are developed truly meet the needs of seniors and their health-care providers. To help achieve this, we have established a research-user advisory board for our team, which is kept involved via regular email updates and an annual one-day Research Retreat. We currently have representatives from 18 different organizations on the board, representing seniors’ groups, health-care providers, policy makers, commercialization partners, and knowledge disseminators (Table 1). We strive to consult board members, as much as possible, during all phases of the research: identifying specific needs for new interventions, planning of studies to test the interventions, evaluation of the test results, and dissemination and utilization of the new knowledge and technologies. The

involvement of the advisory board is also intended to help promote rapid uptake of the research outcomes into governmental policy, health-care practice and the daily life of seniors, by ensuring that key stakeholder organizations are kept aware of our team's research efforts and outcomes.

< insert Table 1 about here >

A second mechanism that we are using to increase involvement of research users involves developing a network of new “gait and balance optimization” (GABO) clinics. The clinics are intended to accelerate the introduction of innovative new assessment and intervention tools into clinical practice, to provide team scientists with much greater opportunity to get feedback from clinicians and their clients, and to provide a readily-available resource for evaluating new approaches and comparing these to existing approaches. To help attain these objectives, the new assessment and intervention tools are integrated into routine care and the treating physical therapist utilizes these tools in his/her clinical decision-making. In addition, the clinicians are encouraged to identify new research questions that will address their practice needs. The first clinic, which is located at the Toronto Rehabilitation Institute, has been in full-scale operation since October 2009 and will serve as the hub for the clinic network. Plans are in place to roll out the first two satellite clinics over the next 2-3 years, with staggered roll-out dates so that we can take advantage of lessons learned at each stage of the process.

Development of inexpensive clinical tools

A common barrier to knowledge translation has been the unavailability of the equipment required to implement the new approaches (Straus et al., 2009b). Thus, for example, in the area of balance assessment, the high equipment costs and technical-expertise requirements associated with “computerized posturography” systems has limited widespread clinical application of this approach (Visser et al., 2008). Similarly, with regard to our research and development efforts, the main such barrier has been the unavailability of a simple, compact inexpensive system for applying balance perturbations. Such a system is needed to assess stepping and grasping balance-recovery reactions, in order to identify specific impairments so that these can be targeted for the most appropriate treatment (e.g. balance training) or other interventions. A balance-perturbation system is also needed to implement the perturbation-based training program described earlier.

In our research, we have used motion platforms to apply balance perturbations; however, such systems tend to be expensive and require considerable space (e.g. 3m x 3m), which may not be available in many clinical settings (Figure 4a). Furthermore, many commercially-available motion platforms do not have a sufficiently large surface to allow stepping reactions, and may not have sufficient range-of-motion, speed or acceleration capacity to evoke stepping and grasping reactions. Manual perturbation techniques [e.g. pushes or pulls applied to the sternum or shoulders (Jöbges et al., 2004; Tinetti, 1986), or use of resistance-band release-from-lean (Rose, 2003) or release-from-hold techniques (Horak et al., 2009)] are the least expensive approach; however, it can be difficult to reliably control the magnitude of the perturbation, to apply perturbations that are large enough to elicit stepping or grasping reactions, or to vary the direction and magnitude of the perturbation in an unpredictable (yet well-controlled) manner. The latter is an important consideration, in order to prevent subjects from learning to use predictive control strategies that are unlikely to be feasible in responding during “real-life” loss-of-balance situations (Maki & McIlroy, 2006).

In our new clinic, we are currently using a simple release-from-lean method [see review by (Hsiao-Wecksler, 2008)], in which the clinician simply pulls a pin to release a cable that is

supporting the subject in a leaning posture (Figure 4b). Although this method is inexpensive, requires minimal equipment and space, and allows the perturbation magnitude to be well controlled, it does have the disadvantage that the direction of the perturbation is predictable. Furthermore, the direction of perturbation is typically restricted to forward loss of balance. Although release-from-lean has also been used to induce backward falling motion in a small number of studies (Hsiao & Robinovitch, 2001; Telonio et al., 2005), one might anticipate that subjects who are fearful of falling may be very reluctant to lean backwards. As for lateral perturbations, our own pilot tests have indicated that it can be very difficult to regulate the trunk angle and weight distribution between the two legs during lateral leaning, and a literature search failed to reveal any studies that have successfully used this approach. We are currently working to develop an improved cable-release approach that introduces directional unpredictability and allows well-controlled perturbations to be readily applied in any direction (details currently unavailable pending submission of a patent application).

The other aspect of assessment involves characterizing the relevant features of the stepping and grasping reactions that are evoked by the perturbation. Fortunately, it appears that the age-related impairments that are the strongest predictors of falling risk are simple behavioral measures that do not require expensive instrumentation to measure. Examples include the number of steps taken to recover equilibrium, the pattern of the steps (e.g. whether an initial forward or backward step is followed by one or more lateral steps), and collisions between the swing foot and stance limb when stepping laterally (Chandler et al., 1990; Maki et al., 2001; Maki & McIlroy, 2006; Rogers et al., 2001; Wolfson et al., 1986). Such measures can be determined from visual observation, performed either in “real time” or “offline” (using video recordings). To expedite the coding and reduce inter-rater variability, we are currently working to develop a very inexpensive automated system that uses web-cams and computer-vision image-processing algorithms (Snoek et al., 2009) to characterize key features of the evoked stepping and grasping reactions.

Commercialization of new products

Commercialization of new products can be a very effective strategy for transferring new technologies into practice (Lane & Flagg, 2010). An added advantage of this approach is that knowledge translation may be further advanced through the publicity and advertising campaigns that are initiated by the involved institutions, manufacturers and vendors. To facilitate widespread knowledge transfer, these interventions need to be as simple and inexpensive as possible. This is certainly the case for the *SoleSensor*® insole described earlier (Figure 1c), which involves a simple and inexpensive design modification. In contrast, the use of vibrating insoles to facilitate footsole sensation (Priplata et al., 2003), which has recently received much attention, is a much more expensive and complicated proposition.

Other examples of commercially-available fall-prevention products that have been developed by team members include the *SturdyGrip*® safety pole described earlier (Figure 2b), as well as the *Access Bathtub* and *Toilevator*® (Figure 5). All of these products were designed, in accordance with universal design principles, to be aesthetically pleasing and to avoid attaching a stigmatizing “disability label”. *SturdyGrip* was the first mass-produced safety pole and has become a standard for numerous “copycat” products that are sold in volumes exceeding 100,000 per year. The *Access Bathtub* reduces the risk of falls in the bath by incorporating features such as built-in grab-bars and a transfer surface. *Toilevator* facilitates toilet transfers and reduces risk of falling during transfers by raising the toilet (Rose, 2003). In contrast to raised toilet seats that clamp onto the top of the existing seat, *Toilevator* fits underneath the toilet and thereby offers a

much safer and less conspicuous way of increasing the toilet height, while an internal plumbing adaptor ensures that the device will fit all of the 200 or so toilet plumbing fixture designs that are used in North America.

< insert Figure 5 about here >

Our approach to technology transfer involves having the companies work closely with the researchers from as early in the process as possible. Of great importance to this process is our capacity to develop attractive, high-quality prototypes that will attract investors. We tend to work with a core “club” of companies. After agreeing to adhere to a confidentiality agreement, each company in the “club” is allowed full access to our research environment and is given priority access to new inventions. Rather than emphasizing early royalty returns (which can be a problem for small and mid-sized companies), we take a longer view and do everything possible to help our licensees with production engineering, testing and marketing. We also strive to minimize legal costs. One of the particularly attractive aspects of our approach is that we have been able to encourage collaborations between companies, which have led to further opportunities to move new inventions into the marketplace.

Modifications to building codes

Another important way to influence the “real world” is through legislation, regulation, codes and standards (Bernard Becke Medical Library, 2010; Pauls & Monson, 2003). Our efforts in this area have included playing a leading role in the development of new built-environment standards under the Accessibility for Ontarians with Disabilities Act (AODA), including many measures to reduce falls through the greater use of functional handrails, safer stair design and better visual markings (www.accessON.ca).

In addition, our team has supported efforts of building-safety advocates, such as Jake Pauls (Pauls, 1991) and Nancy Edwards (Edwards, 2008), to incorporate the results of our handrail studies into building codes. As noted earlier, our studies have led to a set of design recommendations to optimize ability to grasp handrails effectively (Figure 2a), and some of these recommendations have, in fact, been incorporated into ten national and international building codes (Table 2). For example, our results have suggested that handrails should be substantively higher (i.e. minimum recommended height = 91cm) than many building codes had previously allowed (e.g. heights as low as 72cm), in order to maximize the stabilizing forces and moments that are generated by pushing or pulling on the rail during stair descent (Maki et al., 1984; Maki et al., 1985). Our results have also supported the view that the handrail shape and size should allow the fingers to wrap fully around the underside of the rail (i.e. in the manner of a “power grip”, rather than a “pinch” grip), in order to maximize grip strength (Maki, 1985; Maki et al., 2006) and to allow the hand to pull upward on the rail, which appears to be necessary during some phases of the reaction to a stairway loss of balance (Maki et al., 1998). However, there have been some major challenges in improving standards related to handrail shape and size. Although many handrail manufacturers are cognizant of safety concerns, some are resistant to changing the products that they produce. Consequently, committee meetings and hearings to consider building-code changes can often be contentious, and committee members and others with voting power may find it difficult to judge the merits of conflicting experimental data and/or expert testimony (Pauls, 2010).

< insert Table 2 about here >

A review of research on handrails, which drew extensively on our early handrail studies,

was published with the intent to make the task of interpreting research findings and developing or revising standards and codes easier for regulatory authorities (Feeney & Webber, 1994). Another approach to strengthen the case for building-code changes is to perform research to provide more direct evidence that links specific design features to injury-prevention outcomes (Edwards, 2008). To the end, we have developed a computer-vision system that uses video cameras and image-processing software to automatically identify handrail use and “stair events” such as slips, trips, missteps and falls, and to store the associated video images (Snoek et al., 2009). This tool is expected to greatly facilitate evaluation of different handrail designs in “real-life” settings, as previous research of this type has been extremely limited due to the inordinate amount of time and effort required to manually review and analyze the video recordings [over 1200 hours, in one study (Templer et al., 1985)].

Summary

Age-related balance impairment is a major contributor to increased risk of falling. Impairments in balance reactions, such as compensatory stepping and reaching, play a particularly critical role in determining whether or not a balance perturbation actually leads to a fall. Thus, from a clinical perspective, it is important to be able to test these reactions using simple, safe, quick and inexpensive assessment tools. Such tests can then be used to identify high-risk individuals and to pinpoint specific control problems to target for intervention. Our work to date has yielded a range of interventions that can help to counter age-related balance impairments, including new designs of footwear and garments, mobility aids, neuro-prostheses and handrails, as well as two different approaches to training improved ability to execute effective balance reactions (perturbation-based training and visual training).

The strategies that we are using to promote knowledge translation (KT) of our research findings and outcomes involve both “end of grant KT” dissemination methods that are targeted to specific research-user groups and “integrated KT” methods in which we strive to get research users involved in the research process at as early a stage as possible. Our strategies to accomplish the latter include setting up a research-user network and advisory board as well as developing a new network of gait and balance clinics. In general, the research-users have also been involved early on during our KT initiatives that involve development of new balance-testing tools, commercialization of new fall-prevention products and changes to building codes. Ultimately, we anticipate that these efforts will help to prevent falls and thereby reduce the enormous health-care, societal and personal costs resulting from fall-related injury and fear.

Acknowledgments

The studies by the authors described in this paper were supported by grants #NET-54025, #MAT-91865, #MOP-13355, #MOP-77772, #PPP-52016, #PPP-53686 and #IAP79705 from the Canadian Institutes of Health Research, as well as funding from the Canadian Foundation for Innovation, the Ontario Neurotrauma Foundation, the Natural Sciences and Engineering Research Council of Canada, the National Research Council of Canada, the Stairway Manufacturers Association, the Sunnybrook Trust for Medical Research, Sunnybrook Health Sciences Centre, the Toronto Rehabilitation Institute and the University of Toronto (Vision Science Research Program; Health Care Technology and Place Program; Institute of Biomaterials and Biomedical Engineering).

Financial disclosure

Royalties or licensing fees associated with the products mentioned in this article may be used to support the authors' research.

Table 1: Organizations represented on the team's research-user advisory board

Type of organization	Name of organization
seniors' groups	Active Living Coalition for Older Adults
	Canada's Association for the Fifty Plus
associations of health-care providers and caregivers	Canadian Association of Occupational Therapists
	Canadian Geriatrics Society
	Canadian Physiotherapy Association
	Ontario Long-term Care Association
	Regional Geriatric Program of Toronto
	Registered Nurses' Association of Ontario
policy makers	Building Code Committee Members
	Public Health Agency of Canada
	Ontario Public Health Association
commercial partners	A-Tech Instruments
	Hart Mobility
	Health Technology Exchange
	Medilogic
knowledge disseminators	Falls and Mobility Network
	National Initiative for the Care of the Elderly
	Ontario Seniors Health Research Transfer Network

Table 2: U.S. and Canadian building codes influenced by findings from the team's handrail studies

Stairway handrail height and size/shape requirements:

1. International One and Two-Family Dwelling Code (International Code Council)
2. Uniform Building Code (International Conference of Building Officials)
3. Standard Building Code (Southern Building Code Congress)
4. ANSI A117.1, the American National Standard on Accessible and Usable Buildings and Facilities (International Code Council)
5. BOCA National Building Code (Building Officials and Code Administrators)
6. ANSI/NFPA 101 Life Safety Code (National Fire Protection Association)
7. ANSI/NFPA 5000 Building Construction and Safety Code (National Fire Protection Association)

Stairway handrail height requirements:

8. International Residential Code (International Code Council)

Stairway and ramp handrail height and size/shape requirements:

9. International Building Code (International Code Council)
10. National Building Code of Canada (National Research Council)

Figure captions

Figure 1: Methods used to improve balance control by facilitating cutaneous sensation from the footsole: **A.** set-up used in the initial laboratory experiments, in which plastic tubing was adhered to the perimeter of the footsole (Maki et al., 1999); **B.** insole design (*SoleSensor*®) developed on the basis of the experimental findings and tested in the 12-week clinical trial (Perry et al., 2008); **C.** actual commercial product and packaging.

Figure 2: Summary of handrail-research outcomes: **A.** design recommendations for conventional handrails, to optimize the ability of a wide range of users to generate stabilizing force and to reach and grasp the rail effectively (Maki, 1985; Maki et al., 1984; Maki et al., 1985; Maki et al., 1998; Maki et al., 2006); **B.** *SturdyGrip*® safety pole; **C.** *LifeRail* (C.1-C.4) and double-rail (C.5) handrail systems (Gorski, 2005), in which the upper rail is intended to be “hugged” under the arm (C.1) [note: the lower rail can also be used in a conventional manner (C.2) but the upper surface of *LifeRail* is not designed for effective grasping (C.3); the double-rail system (C.5) permits both upper and lower rails to be grasped effectively, while still allowing for the upper rail to be hugged]; **D.** handrail cueing system (Scovil et al., 2007b), in which a proximity detector is used to trigger a visual cue (flashing of light-emitting diodes mounted within the translucent railing) and/or verbal prompt to use the rail (issued via speakers located in the railing or mounting brackets). Adapted from (Maki et al., 2008a).

Figure 3: Photographs showing a standard pickup walker (**A**) and the design changes that were made so as to reduce restrictions on lateral stepping reactions (Cheng et al., 2008). The overlaid line drawings highlight the arched strut that replaced the lower horizontal bar (**B**) and the extension of the walker length that served to move the rear posts away from the feet (**C**). Adapted from (Maki et al., 2008a).

Figure 4: Balance-perturbation methods: **A.** motion-platform system, and **B.** release-from-lean cable-release system. **A** is one example of the multi-directional platforms that we have used in our various research studies of stepping and grasping reactions (this particular platform is driven by pneumatic cylinders; our other platforms are motor driven). **B** shows the cable-release system that our clinical partners are currently using to induce forward falling motion and forward-directed compensatory stepping reactions (subjects are instructed to lean forward until the cable supports their body, and this cable is then released at an unpredictable moment in time by pulling a pin).

Figure 5: Examples of other fall-prevention products that have been developed by team members and commercialized successfully: **A.** *Access Bathtub* and **B.** *Toilevator*® toilet raiser. In **A**, the person is sitting on the built-in transfer surface; the built-in grab-bars are mounted on the other side and at the end of the tub (behind the person). **B** shows how the device is mounted underneath the toilet, to achieve a much more stable and less conspicuous system than conventional toilet raisers, which are clamped onto the top of the toilet seat.

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Figure 1: Methods used to improve balance control by facilitating cutaneous sensation from the footsole: **A.** set-up used in the initial laboratory experiments, in which plastic tubing was adhered to the perimeter of the footsole (Maki et al., 1999); **B.** insole design (SoleSensor[®]) developed on the basis of the experimental findings and tested in the 12-week clinical trial (Perry et al., 2008); **C.** actual commercial product and packaging.

Figure 2: Summary of handrail-research outcomes: A. design recommendations for conventional handrails, to optimize the ability of a wide range of users to generate stabilizing force and to reach and grasp the rail effectively (Maki, 1985; Maki et al., 1984; Maki et al., 1985; Maki et al., 1998; Maki et al., 2006); B. SturdyGrip® safety pole; C. LifeRail (C.1-C.4) and double-rail (C.5) handrail systems (Gorski, 2005), in which the upper rail is intended to be “hugged” under the arm (C.1) [note: the lower rail can also be used in a conventional manner (C.2) but the upper surface of LifeRail is not designed for effective grasping (C.3); the double-rail system (C.5) permits both upper and lower rails to be grasped effectively, while still allowing for the upper rail to be hugged]; D. handrail cueing system (Scovil et al., 2007b), in which a proximity detector is used to trigger a visual cue (flashing of light-emitting diodes mounted within the translucent railing) and/or verbal prompt to use the rail (issued via speakers located in the railing or mounting brackets). Adapted from (Maki et al., 2008a).

Figure 3: Photographs showing a standard pickup walker (A) and the design changes that were made so as to reduce restrictions on lateral stepping reactions (Cheng et al., 2008). The overlaid line drawings highlight the arched strut that replaced the lower horizontal bar (B) and the extension of the walker length that served to move the rear posts away from the feet (C). Adapted from (Maki et al., 2008a).

Figure 4: Balance-perturbation methods: **A.** motion-platform system, and **B.** release-from-lean cable-release system. **A** is one example of the multi-directional platforms that we have used in our various research studies of stepping and grasping reactions (this particular platform is driven by pneumatic cylinders; our other platforms are motor driven). **B** shows the cable-release system that our clinical partners are currently using to induce forward falling motion and forward-directed compensatory stepping reactions (subjects are instructed to lean forward until the cable supports their body, and this cable is then released at an unpredictable moment in time by pulling a pin).

Figure 5: Examples of other fall-prevention products that have been developed by team members and commercialized successfully: **A.** *Access Bathtub* and **B.** *Toilevator®* toilet raiser. In **A**, the person is sitting on the built-in transfer surface; the built-in grab-bars are mounted on the other side and at the end of the tub (behind the person). **B** shows how the device is mounted underneath the toilet, to achieve a much more stable and less conspicuous system than conventional toilet raisers, which are clamped onto the top of the toilet seat.